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Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
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D vice inspection

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Device Inspection

The present invention relates to methods of inspection useable in the manufacture of devices by lithographic techniques and to device inspection apparatus.

In a manufacturing process using a lithographic projection apparatus, a pattern (e.g. in a mask) is imaged onto a substrate that is at least partially covered by a layer of radiation-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g. an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemical-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the individual devices can be mounted on a carrier, connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4, incorporated herein by reference.

The inspection step after development of the resist, commonly referred to as metrology, serves two purposes. Firstly, it is desirable to detect any target areas where the pattern in the developed resist is faulty. If a sufficient number of dies are faulty, the wafer can be stripped of the patterned resist and re-exposed, hopefully correctly, rather than making the fault permanent by carrying out a process step, e.g. an etch, with a faulty pattern. Secondly, the measurements may allow errors in the lithographic apparatus, e.g. in illumination settings or exposure times, to be detected and corrected for subsequent exposures.

A metrology measurement may be used to determine the overlay error between two layers of a wafer, or may be used to determine focus errors or the critical dimension (CD) of features of a particular layer of the wafer (usually the uppermost layer). There are a variety of ways in which the metrology measurement may be obtained. Typically, these are

performed in an apparatus which is separate from the lithographic apparatus. Measurements performed in a separate apparatus are commonly referred to as off-line. A single off-line apparatus may be used to perform metrology measurements for wafers produced by several lithographic apparatus.

One known off-line metrology apparatus, used to measure overlay is based upon imaging of boxes printed on the wafer, a first box being printed on a first layer and a second box being printed on a second layer. This apparatus may also be used to measure focus errors. The apparatus is commonly referred to as box-in-box (or frame-in-frame). A disadvantage of the box-in-box apparatus is that its general accuracy is limited because it relies upon single line image detection.

A second known off-line metrology apparatus comprises a scanning electron microscope (SEM). This provides very high resolution measurements of the surface of a wafer, and is used for CD measurements. A disadvantage of this apparatus is that it is slow and expensive.

A third known off-line metrology apparatus is known as a scatterometer. This provides measurement of CD and/or overlay. In a scatterometer, white light is reflected by periodic structures in the developed resist and the resulting reflection spectrum at a given angle detected. The structure giving rise to the reflection spectrum is reconstructed, e.g. using Rigorous Coupled-Wave Analysis (RCWA) or by comparison to a library of spectra derived by simulation. However, the reconstruction of the structure is computationally very intensive and the technique can suffer from low sensitivity and poor repeatability.

It is an object of the present invention to provide device inspection which overcomes at least one of the above disadvantages.

According to the invention there is provided a method of device inspection, the method comprising providing an asymmetric marker on a device to be inspected, the form of asymmetry of the marker being dependent upon the parameter to be inspected, directing light at the marker, obtaining a first measurement of the position of the marker via detection of diffracted light of a particular wavelength or diffraction angle, obtaining a second measurement of the position of the marker via detection of diffracted light of a different wavelength or diffraction angle, and comparing the first and second measured positions to determine a shift indicative of the degree of asymmetry of the marker.

The first and second position measurements may comprise detection of diffracted light having different diffraction angles but the same wavelength. Alternatively, the first and second position measurements may comprise detection of diffracted light having the same

diffraction angle but different wavelengths. In a further alternative, the first and second position measurements may comprise detection of diffracted light having different diffraction angles and different wavelengths.

The marker may comprise one or more diffraction gratings and the diffraction angles may comprise diffraction orders.

The marker may comprise a first diffraction grating provided in a first layer of the device, and a second diffraction grating provided in a second lower layer of the device, the first diffraction grating and the second diffraction grating having the same pitch and being provided one over the other such that the light is diffracted by both of the gratings in combination.

The marker may comprise a first diffraction grating provided in a first layer of the device, and a second diffraction grating provided in a second lower layer of the device, the first diffraction grating and the second diffraction grating having different pitches each selected to give rise to strong diffraction at different diffraction orders, such that a measurement of the position of the first diffraction grating is provided by measuring one diffraction order and a measurement of the position of the second diffraction grating is provided by measuring the other diffraction order, the shift indicating the overlay of the first and second layers.

The term 'strong diffraction' is intended to mean that the diffraction is sufficiently strong to be measured, and is preferably stronger than diffraction from both of the gratings in combination.

The marker may comprise one phase grating arranged to measure the focus accuracy of a lithographic projection apparatus, the method comprising providing on a mask of the lithographic projection apparatus a phase grating having a substructure which includes a phase jump of substantially 90 degrees, the phase jump being of opposite sign for adjacent periods of the grating, the pitch of the substructure being selected such that a focus error will cause the phase grating to shift when projected onto the device by the lithographic apparatus, adjacent periods of the phase grating being shifted in opposite directions giving rise to an asymmetry which is measured by the shift.

The marker may comprise one diffraction grating arranged to measure the critical dimension of a lithographic projection apparatus, the method comprising providing on the device a diffraction grating having a substructure with a pitch at, or of the order of, the limit of resolution of the lithographic projection apparatus, the substructure being arranged to form an additional line of the diffraction grating which renders the diffraction grating

asymmetric, changes of the critical dimension modifying the effective reflectivity of the substructure thereby modifying the asymmetry of the diffraction grating, the modified asymmetry being detected as the shift.

The invention also provides a device inspection apparatus, the apparatus comprising a light source arranged to direct light at an asymmetric marker provided on a device, a detector arranged to detect light diffracted from the marker with a particular wavelength or diffraction angle thereby providing a measurement of the position of the marker, a second detector arranged to detect light diffracted from the marker with a different wavelength or diffraction angle thereby providing a second measurement of the position of the marker, and comparison means arranged to compare the measured positions to determine a shift.

The invention also provides a device inspection apparatus, the apparatus comprising a light source arranged to direct light at a phase grating provided on a device, a detector arranged to detect light diffracted from the phase grating, and processing means arranged to obtain inspection information using the detected diffracted light.

Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal display panels, thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "target portion", respectively.

In the present document, the terms “light”, “radiation” and “beam” are used to encompass all types of electromagnetic radiation, including ultraviolet radiation (*e.g.* with a wavelength of 365, 248, 193, 157 or 126 nm) and EUV (extreme ultra-violet radiation, *e.g.* having a wavelength in the range 5-20 nm), as well as particle beams, such as ion beams or electron beams.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying schematic drawings in which:

Figure 1 depicts a lithographic projection apparatus that may be used in the performance methods according to the invention;

Figure 2 is a flow diagram of a lithographic process according to an embodiment of the invention;

Figures 3 and 4 depict metrology units according to the present invention;

Figure 5 depicts a metrology grating used in a method according to the present invention;

Figures 6 depicts a metrology grating used in an alternative method according to the present invention;

Figure 7 schematically illustrates coupling between gratings;

Figure 8 depicts a metrology grating used in an alternative method according to the present invention;

Figures 9 and 10 depict a metrology grating used in an alternative method according to the present invention;

Figures 11 and 12 illustrate a method which may be used in combination with the present invention to reduce measurement errors;

Figures 13 and 14 depict a metrology grating used in an alternative method according to the present invention;

Figures 16 to18 depict a metrology grating used in an alternative method according to the present invention, together with results obtained using that grating;

Figures 19 to 21 depict a metrology grating and metrology unit used in an alternative method according to the present invention; and

Figure 22 shows schematically how the invention may be implemented without using gratings.

In the Figures, corresponding reference symbols indicate corresponding parts.

Lithographic Projection Apparatus

Figure 1 schematically depicts a lithographic projection apparatus useable in methods according to the invention. The apparatus comprises:

- a radiation system Ex, IL, for supplying a projection beam PB of radiation (*e.g.* DUV radiation), which in this particular case also comprises a radiation source LA;
- a first object table (mask table) MT provided with a mask holder for holding a mask MA (*e.g.* a reticle), and connected to first positioning means for accurately positioning the mask with respect to item PL;
- a second object table (substrate table) WT provided with a substrate holder for holding a substrate W (*e.g.* a resist-coated silicon wafer), and connected to second positioning means for accurately positioning the substrate with respect to item PL;

- a projection system ("lens") PL (*e.g.* a refractive lens system) for imaging an irradiated portion of the mask MA onto a target portion C (*e.g.* comprising one or more dies) of the substrate W.

As here depicted, the apparatus is of a transmissive type (*e.g.* has a transmissive mask). However, in general, it may also be of a reflective type, for example (*e.g.* with a reflective mask). Alternatively, the apparatus may employ another kind of patterning means, such as a programmable mirror array of a type as referred to above.

The source LA (*e.g.* an excimer laser) produces a beam of radiation. This beam is fed into an illumination system (illuminator) IL, either directly or after having traversed conditioning means, such as a beam expander Ex, for example. The illuminator IL may comprise adjusting means AM for setting the outer and/or inner radial extent (commonly referred to as σ-outer and σ-inner, respectively) of the intensity distribution in the beam. In addition, it will generally comprise various other components, such as an integrator IN and a condenser CO. In this way, the beam PB impinging on the mask MA has a desired uniformity and intensity distribution in its cross-section.

It should be noted with regard to Figure 1 that the source LA may be within the housing of the lithographic projection apparatus (as is often the case when the source LA is a mercury lamp, for example), but that it may also be remote from the lithographic projection apparatus, the radiation beam which it produces being led into the apparatus (e.g. with the aid of suitable directing mirrors); this latter scenario is often the case when the source LA is an excimer laser. The current invention and Claims encompass both of these scenarios.

The beam PB subsequently intercepts the mask MA, which is held on a mask table MT. Having traversed the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto a target portion C of the substrate W. With the aid of the second positioning means (and interferometric measuring means IF), the substrate table WT can be moved accurately, *e.g.* so as to position different target portions C in the path of the beam PB. Similarly, the first positioning means can be used to accurately position the mask MA with respect to the path of the beam PB, *e.g.* after mechanical retrieval of the mask MA from a mask library, or during a scan. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (course positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in Figure 1. However, in the case of a wafer stepper (as opposed to a step-and-scan apparatus) the mask table MT may just be connected to a short stroke actuator, or may be fixed.

The depicted apparatus can be used in two different modes:

In step mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (*i.e.* a single "flash") onto a target portion C. The substrate table WT is then shifted in the x and/or y directions so that a different target portion C can be irradiated by the beam PB;

In scan mode, essentially the same scenario applies, except that a given target portion C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", *e.g.* the y direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is simultaneously moved in the same or opposite direction at a speed $V = Mv$, in which M is the magnification of the lens PL (typically, $M = 1/4$ or $1/5$). In this manner, a relatively large target portion C can be exposed, without having to compromise on resolution.

Figure 2 is a flow diagram of a lithographic process of which the present invention may form part. Prior to the exposure step S4, which may be carried out using a lithographic apparatus such as described above with relation to Figure 1, a substrate, *e.g.* a silicon wafer, undergoes a priming step S1, spin coating step S2 to coat it with a layer of resist and a soft bake S3 to remove solvents from the resist. After exposure, the wafer undergoes a post-exposure bake S5, a development step S6 during which the exposed or unexposed resist (depending on whether the resist is positive or negative) is removed and a hard bake S7, prior to an inspection step S8. The inspection step S8 includes various different measurements and inspections and according to the invention includes a metrology step described further below. If the wafer passes inspection, a process step S9 is carried out. This may involve etching the areas of the substrate not covered by resist, deposition of a product layer, metallisation, ion implantation, etc. After the process step S9 the remaining resist is stripped S10 and a final inspection S11 carried out before the process resumes for another layer. In case a substrate fails an inspection at S8, it may be directed directly to a stripping step S10 and another attempt to print the same process layer made. Although it is preferred that the inspection step be performed after the hard bake S7, in some instances it may be performed after the post-exposure bake S5 or even directly after exposure S4. The manner in which this may be done is described further below.

In the inspection step a metrology unit of the type shown in Figure 3 is used. The metrology unit corresponds with a prior art alignment unit, for example as described in WO 98/39689, which is incorporated herein by reference. Referring to Figure 3, a substrate mark is provided in the form of a grating, denoted P_1. An illumination beam b having a wavelength λ incident on the grating is split up into a number of sub-beams

extending at different angles α_n (not labelled) to the normal on the grating, which angles are defined by the known grating formula:

$$Sin\alpha_n = \frac{n\lambda}{P}$$

where n is the diffraction order number and P the grating pitch.

The path of the sub-beams reflected by the grating incorporates a lens system L_1 which converts the different directions of the sub-beams into different positions u_n of these sub-beams in a plane 73:

$$u_n = f_1\alpha_n$$

In this plane means are provided for further separating the different sub-beams. To this end, a plate may be arranged in this plane, which is provided with deflection elements in the form of, for example, wedges. In Figure 3 the wedge plate is denoted by WEP. The wedges are provided on, for example the rear side of the plate. A prism 72 can then be provided on the front side of the plate, with which an incident beam coming from the radiation source 70, for example a He-Ne laser, can be coupled into the metrology sensor. This prism can also prevent the 0-order sub-beam from reaching the detectors (the 0-order sub-beam is not desired at the detectors). The number of wedges corresponds to the number of sub-beams which is to be used. In the embodiment shown, there are six wedges per dimension plus orders so that the sub-beams can be used up to and including the 7^{th}-order. All wedges have a different wedge angle so that an optimal separation of the different sub-beams is obtained.

A second lens system is arranged behind the wedge plate. This lens system images the mark P_1 in the plane reference plate RGP. In the absence of the wedge plate, all sub-beams would be superimposed in the reference plane. Since the different sub-beams through the wedge plate are deflected at different angles, the images formed by the sub-beams reach different positions in the reference plane. These positions X_n are given by:

$$X_n = f_2\gamma_n$$

in which γ is the angle at which a sub-beam is deflected by the wedge plate.

At these positions, reference gratings are provided. A separate detector is arranged behind each of the reference gratings. The output signal of each detector is dependent upon the extent to which the image of the substrate grating P_1 coincides with the relevant reference grating. The pitch of each grating is adapted to the order number of the associated sub-beam incident on that grating. As the order number increases, the pitch decreases.

Figure 4 shows a metrology unit, of the type shown in Figure 3, arranged to use two wavelengths. In figure 4 the reference numeral 160 denotes a polarisation sensitive beam splitter. This beam splitter receives a first beam b having a first wavelength λ_1, for example 633 nm, from a He-Ne laser, and having a first direction of polarisation and passes this beam to the substrate alignment mark P_1. Incident on this beam splitter is also a second alignment beam b_5, which has a second wavelength λ_2, for example 532nm and comes from a YAG laser preceding a frequency doubler. The beam b_5 has a direction of polarisation which is perpendicular to that of the beam b so that the beam b_5 is reflected to the substrate mark P_1. It has been ensured that the chief rays of the beams b and b_5 are made to coincide by the beam splitter so that these beams will be passed as one beam to the mark P_1. After reflection by the mark, the beams b and b_5 are split again by the beam splitter. A separate unit 170, 180 is present for each of these beams. Each of these units emits an incident beam and receives, via the beam splitter, the sub-beams of the different diffraction orders coming from the substrate mark. In each of these units, images of the substrate mark are formed on different reference gratings and with different sub-beams, as has been described with reference to Figure 3. To this end, each unit is provided with a lens system L_1, L_2 (L_1', L_2'), a wedge plate WEP (WEP'), a plate with reference gratings RGHP (RGP'), a number of detectors 90-96 (90'-96') and a radiation source 70 (70') whose beam is coupled into the system via a coupling prism 72 (72').

A metrology unit of the type shown in Figure 3 or in Figure 4 is conveniently located to allow in-line metrology to be performed. In one implementation of the invention the metrology unit is located in a track (a track carries wafers to and from storage, and in addition bakes and develops wafers). The metrology unit is located downstream of post-exposure baking and developing, such that patterns exposed in the resist layer are clearly visible to the unit. In an alternative implementation the metrology unit is located adjacent to, and is connected to, the track. Wafers pass from the track to the metrology unit and are returned to the track following measurement. The connection to the track is via a conventional output port, and is located downstream of post-exposure baking and developing. In a further alternative implementation the metrology unit is provided in a

separate apparatus that is not connected to the track, i.e. off-line. The metrology unit may alternatively be provided within the lithographic projection apparatus (this implementation is described further below).

During production (i.e. in-line) a grating is exposed onto a wafer during projection of product features onto the wafer. The grating may be located in a specific designated non-product area, or may be located in scribe lines which separate product structures. The wafer is developed, baked and processed. The grating may be used during inspection for focus metrology or for critical dimension metrology. Inspection may occur at any convenient time at indicated above in relation to Figure 2.

Where overlay metrology is required, processing of the grating and product features is completed so that they are permanently held on the wafer. A layer of resist is spun onto the wafer, and a subsequent layer of product features is exposed onto the wafer, together with a second grating. The second grating is located above the first grating, and measurements of the positions of the first and second gratings (for example detected individually or as a composite grating) are made using different diffraction orders or wavelengths of the metrology unit. These measurements are used to determine the overlay.

In one embodiment of the invention the gratings have the configuration shown in figure 5. There is some vertical separation between the gratings, for example due to an oxide layer located over the first grating. The second grating has the same pitch *P* as the first grating, although each line of the second grating is narrower. The second grating is deliberately displaced relative to the first grating, by a shift *D*. The two gratings can be considered as one composite grating with a certain overall shape. The composite grating includes an asymmetry caused by the deliberate shift *D* between the first and second gratings.

Although each line of the second grating shown in Figure 5 is narrower than the first grating, it is not essential that this is the case. All that is required is that some portion of the second grating is visible to the metrology unit (for example, each line of the first grating may be wider than those of the second grating, the second grating being visible due to the deliberate shift *D*).

As a result of the asymmetry the apparent position, as measured by the metrology unit, of the composite grating is shifted. This shift x_{shift} is dependent upon the detected wavelength (λ) and diffraction order *n*. Since the shift is wavelength and diffraction order dependent, this allows information regarding the shift to be obtained by comparing signals detected for different wavelengths and diffraction orders. Where the shift includes the

deliberate shift D and a shift caused by inaccuracies of the lithographic projection apparatus (e.g. overlay errors), the size and sign of the shift cause by the inaccuracies can be measured by comparing that shift with the deliberate shift. This provides in-line metrology measurements of the wafer. It will be appreciated that the deliberate shift D is one of many ways in which an asymmetry may be introduced between the first and second gratings in order to facilitate in-line metrology measurements. Alternative ways of introducing the asymmetry are described further below.

During the metrology measurement the substrate is scanned relative to the metrology unit. It will be appreciated that the substrate may be fixed, with for example reference gratings (RGP in Figure 3) of the metrology unit being scanned; all that is required is that there is relative movement between the substrate and the reference gratings. The scan is transverse to the direction of the lines of the grating, and has the effect that an image of the grating P_1 passes over each reference grating RGP (RGP') thereby generating a sinusoidal signal at the detectors 90-96 (90'-96'). The sinusoidal signal is recorded as a function of the position of the substrate, the centre of the grating P_1 being determined as the position at which the sinusoidal signals from each of the detectors pass through peaks.

Scanning of the substrate is achieved by scanning the substrate table (WT in Figure 1). Movement of the substrate table will introduce a small unknown position error Δx_{stage} of the substrate table. Taking account of this error, during scanning the detected metrology signal as a function of time t can be written as:

$$I(n,\lambda,t)=a+b\cos\left[4\pi n\frac{vt+\Delta x_{stage}(t)+x_{shift}(n,\lambda,D)}{P}\right]$$

where n is the diffraction order, λ is the wavelength, a and b are constants, and Δx_{stage} is the difference between the intended location vt of the substrate table and the actual location of the substrate table. For low-frequency errors the substrate table position error shows up as a position error in the measured position. Curve fitting, for example using a least squares fit, yields the following measured positions:

$$x_{measured}(n,\lambda)=\Delta x_{stage}+x_{shift}(n,\lambda,D)$$

Measuring the difference in measured position between any order/color yields a Shift-between-Orders *SbO*:

$$SbO(m,n,\lambda_1,\lambda_2,D) = x_{measured}(m,\lambda_1) - x_{measured}(n,\lambda_2) \\ = x_{shift}(m,\lambda_1,D) - x_{shift}(n,\lambda_2,D)$$

where m and n indicate diffraction orders, and λ_1 and λ_2 indicate wavelengths. It can be seen that the position error Δx_{stage} of the substrate table cancels out when the *SbO* is measured. This is because to a degree of accuracy sufficient for the purposes of the measurement it is independent of the diffraction order or wavelength. As indicated in the above equation, the term 'shift-between-orders' (*SbO*) refers to a difference in measured position which arises when different diffraction orders are measured or when different wavelengths are measured for the same diffraction order. For ease of terminology the term does not specifically refer to different wavelengths. This is not intended to imply at any point in this document that differences in measured positions arising from different wavelength measurements are excluded.

The selected orders and wavelengths are kept fixed so that the *SbO* is a function only of the offset *D*. Due to the symmetry of the setup:

$$SbO(D) = -SbO(-D)$$

In order to measure overlay two composite gratings are printed with opposite offsets *D* and –*D*. In case of perfect overlay the sum of the *SbO*'s would be zero. This yields a simple overlay metrology measurement, which indicates when, to the resolution of the metrology unit (for example less than 1nm), the overlay is perfect. However, it will almost certainly be the case that the overlay is not perfect, whereupon the overlay error is quantified to provide a useful metrology measurement.

The overlay error is quantified by comparing the error with a known small offset. The overlay error *OV* can be expressed as follows:

$$SbO(D) + SbO(-D) = 2OV\frac{\mathrm{d}SbO}{\mathrm{d}x}$$

In order to quantify the overlay error it is necessary to determine how rapidly the *SbO* varies for small changes in the shift *D*, i.e. as a function of the overlay error . This sensitivity is measured with a third grating that is printed with a shift $D+d$ where *d* is a small known offset. Assuming linearity, the sensitivity of the *SbO* for small displacements is given by:

$$\frac{\mathrm{d}SbO}{\mathrm{d}x} = \frac{SbO(D+d) - SbO(D)}{d}$$

The value of *d* is determined by conflicting requirements: on one hand it must be large to minimize noise but on the other hand it must be sufficiently small to guarantee linearity. Typically, *d* should be the same size, or slightly larger, than the largest overlay error that it is desired to be able to measure, for example *d* could be of the order of hundreds of nanometers. Other suitable values may be used. The overlay follows from the following measurement on the three gratings:

$$OV = \frac{d}{2}\frac{SbO(D) + SbO(-D)}{SbO(D) - SbO(D+d)}$$

This measurement can be done for many order/wavelength pairs, although in practice only the order/wavelength pair with the highest sensitivity need be used.

Each grating may have a size of a few tens of square microns. There may be an exclusion zone of a few microns around each grating. The gratings may be provided in a scribe lane adjacent to a corner of a die. It may be desired to perform metrology measurements in more than one corner of the die. One manner in which this may be done is by providing the three gratings in each corner in which measurement is required. Alternatively, to reduce the number of gratings, thereby freeing space for other elements, three gratings may be provided for one corner of the die and only single gratings provided in other corners for which measurements are required (i.e. one grating per corner). Overlay measured using the single grating is quantified using the sensitivity measurement obtained using the three gratings. This takes advantage of the fact that the sensitivity of the measurement does not vary significantly between corners of the die.

In a variation of the embodiment of the invention, a pair of gratings may be used to obtain the overlay metrology measurement, instead of three gratings. This is advantageous

because it occupies a lesser amount of scribe lane area. The reduction to two gratings is possible due to the realisation that the sensitivity quantification offset d may be incorporated into one of the deliberate offsets D, $-D$.

In general terms the detected shift between orders may be considered to be caused by an offset Δx between the gratings and a scaling factor k which depends upon the 'depth' of the gratings and their separation ('z' in Figure 5). This can be expressed as:

$$SbO = k\Delta x$$

where the offset is a combination of a deliberate offset D and an overlay error OV:

$$\Delta x = D + OV$$

If two gratings are used then this provides two shift between order measurements, which provides sufficient information to allow the two unknown values k, OV to be determined (the deliberate offset D is known from the design of the mask from which the gratings are projected):

$$SbO_1 = k(D + OV)$$

$$SbO_2 = k(D - OV)$$

This is equivalent to making the sensitivity quantification offset d equal to $(+D\text{-}2D)$. The overlay follows from the measurement on the two gratings:

$$OV = \frac{SbO_2 + SbO_1}{SbO_2 - SbO_1}$$

The above description relates to an embodiment of the invention in which a composite grating is formed using two overlapping gratings having the same pitches. Resist and product gratings of equal pitches, however, yield a strong coupling between the gratings. Due to this coupling, the SbO is not only a function of overlay it is also affected by vertical grating separation (z in Figure 5), wavelength, and grating shape. For this reason calibration based upon two or more composite gratings is required.

In an alternative embodiment of the invention gratings are used which are not coupled (strictly speaking all gratings are coupled to a greater or lesser extent; the term 'not coupled' is intended to mean that the size of the signal arising from the coupling is much smaller than that arising individually from each grating). This alternative embodiment is based on spatial frequency multiplexing, and uses gratings with different pitches of (P/N) and (P/M). P may be of the order of tens of microns. These pitches are selected to be compatible with metrology unit reference gratings which have pitches of P/(1,2...7). It will be appreciated that any other suitable pitches may be used. The measured SbO is

directly proportional to overlay, and hence a calibration with multiple targets is no longer necessary.

The alternative embodiment of the invention is based upon the fact that diffraction from a grating of a given pitch, e.g. P/6 will be detected strongly at the metrology unit reference grating which has the same pitch. Diffraction from a grating of a different pitch, e.g. P/7 will be detected strongly at the metrology unit reference grating which has that pitch. This means that it is possible to detect separately gratings in the product layer and the resist layer even if they lie over one another, by looking at different diffraction orders. The difference between the measured positions, the SbO, indicates directly the overlay of the gratings.

A grating running in the x-direction is exposed and processed on the wafer. The resulting, fixed grating, is referred to herein as being in the product layer. The grating has a pitch P/N where N is one of the following: 1, 2....7. Before the wafer is exposed, this grating is covered with a resist film. The reflected field prior to exposure can be expressed as:

$$E(x,y)=\left[\overline{F}+F_N(x,y)\right]$$

The subscript N indicates the periodicity of P/N and $\overline{F}$ is the average complex value of the reflected field (the so called 0-order). The complex amplitudes of the other orders follow from a Fourier decomposition of F_N. The resist is then exposed with a higher-order grating with pitch P/M, where M is one of the following: 1,2,....7 ($M \neq N$). This produces, after development, a resist grating on top of the product grating as shown in Figure 6. In Figure 6 the product grating has a pitch of P/6 (i.e. N=6), and the resist grating has a pitch of P/7 (i.e. M=7).

The resist grating perturbs the field reflected by the product grating, so that it is no longer in the simple form indicated above. Assuming an overlay error of x_0 between the product grating and the resist grating, the reflected field may be expressed in the following form:

$$\begin{aligned} E(x,y) &= \left[\overline{F}+F_N(x,y)\right]\cdot\left[\overline{G}+G_M(x-x_0,y)\right] \\ &= \overline{F}\overline{G}+\overline{G}F_N(x,y)+\overline{F}G_M(x-x_0,y)+F_N(x,y)G_M(x-x_0,y) \end{aligned}$$

In order to provide a graphical explanation of these terms, they are shown in Figure 7 for two transmission gratings F and G with different pitches of N and M respectively (transmission gratings are used in place of reflection gratings for ease of illustration).

The term $\overline{F}.\overline{G}$ is a zero order transmitted by F and G.

The terms used for overlay metrology are $\overline{G}F_N(x,y)$ and $\overline{F}G_M(x-x_0,y)$. The term $F_N(x,y)G_M(x-x_0,y)$, which comprises orders that have been diffracted by both gratings, is

not used for metrology in this embodiment. These terms have each been diffracted by only one grating, the grating F and the grating G respectively. The position of the product grating is measured by the term $\overline{G}F_N(x,y)$ and the position of the resist grating is measured by the term $\overline{F}G_M(x-x_0,y)$, the difference between the two measured positions indicating the overlay error. In other words, the SbO of $\overline{G}F_N(x,y)$ and $\overline{F}G_M(x-x_0,y)$ is directly equal to the overlay. The metrology unit measures the position of the product grating by monitoring only gratings having a pitch of P/6, and then subsequently measures the position of the resist grating by monitoring only gratings having a pitch of P/7. The difference between the positions of the gratings indicates the overlay error between the resist layer and the product layer.

The alternative embodiment of the invention may be considered as a form of spatial frequency multiplexing: the resist and product gratings can be measured separately by the metrology unit since they have different spatial frequencies. The metrology unit is able to measure these separately since it is arranged to direct different diffraction orders to different detectors, as described above in relation to Figure 3.

It will be appreciated that gratings having pitches other than P/(N or M) may be used. Any suitable pitch may be used, with the proviso that N and M are not equal, and that they are selected such that mixing between diffraction orders will not lead to a combined signal (Moiré signal) with the same frequency as a signal which is detected by the metrology unit. For example, N=2 and M=4 is not recommended since the mixed signal will interfere with the signal from the product grating (this would work, but would provide lesser accuracy). Pitches may be chosen which will not lead to a problematic combined signal: the coupled term $F_N(x,y)G_M(x-x_0,y)$ comprises orders that have been diffracted by both gratings (this is shown as the lowermost beam in Figure 7). It is desired to minimise the coupling term, since it may generate spatial frequency components at the measurement frequencies M and N. For example, in Figure 7 the lowermost beam will introduce an error into measurement of the uppermost beam, since both beams have the same spatial frequency.

The pitches are chosen such that N and M have no common divisor (for example N=6 and M=7). When this is done a first combined signal folds back to the detected order M and the a second combined signal solutions folds back to the detected order N. So again assuming N=6 and M=7, n=7 and m=(-5;-7) fold back to detected order M, and m=6 and n=(-6,-8) fold back to detected order N. The folded back signal will be very weak due to the high values of m and n.

The folded back signal caused by the coupled term will, if the above rule is followed, in most instances be of sufficiently low amplitude that it will not introduce any significant error into the overlay metrology measurement. One reason why the high frequency term is small in amplitude is that, due to processing of the wafer, the form of the gratings is closer to a sine wave than a square wave thereby suppressing higher harmonics.

If desired, coupling between the gratings can be minimised in a further alternative embodiment of the invention by ensuring that there is no spatial overlap between the product grating and the resist gratings. This may be achieved by displacing the resist grating so that it lies adjacent the product grating, as shown in Figure 8. The resist grating and the product grating have different pitches as shown. Since the gratings do not overlap, to a first approximation there is no coupling between the gratings. The position of each grating in the x-direction is determined using the metrology unit, the difference between the positions indicating the overlay error.

A disadvantage associated with the grating arrangement shown in Figure 8 is that if the x-axis of the wafer is not exactly parallel with the x-axis of the metrology unit, then scanning of the gratings during metrology measurement will lead to an error. This is because the metrology unit will, due to the rotation measure one of the gratings as being shifted in the x direction and the other grating as being shifted in the $-x$ direction. This error can be cancelled out by providing a second pair of gratings in which the positions of the gratings have been swapped over. The swapping means that the sign of the error measured by the metrology unit is opposite and can be cancelled out from the measurement.

An alternative way of solving the problem of rotation induced error is to split the resist grating and the product grating into non-overlapping parts as shown in Figure 9. Advantageously this embodiment of the invention in addition allows detection of large overlay errors in a perpendicular direction, as described below in relation to Figures 9 to 13.

Referring to Figure 9, a product grating is separated into three parts, and a resist grating is separated into two parts. The parts are arranged so that they do not overlap with the each other. The product grating and the resist grating are both symmetric about an axis in the x-direction which bisects both gratings. This configuration eliminates rotation induced errors.

The direction of measurement of the metrology unit, i.e. the direction in which the wafer is scanned during measurement, is indicated as x in Figure 9 (this is conventional notation). The product grating has a pitch of P/7, whereas the resist grating has a pitch of P/6 (P is of

the order of 10 microns). The direction in the plane of the wafer which is perpendicular to the direction of measurement is indicated as y in Figure 9. The separation of each grating into three separate parts is such that the product grating and the resist grating are periodic in the y direction. They have the same pitch Q but they are mutually 180° degrees phase-shifted as shown in Figure 9. Since the product grating and the resist grating are spatially separated, there is virtually no coupling between them (a small degree of residual coupling may remain). The position of the resist grating is measured using the metrology unit, and the position of the product grating is separately measured using the metrology unit, the difference in positions indicating the overlay error (as previously stated the measurement is performed in the x-direction).

The use of two dimensional gratings as shown in Figure 9 has the advantage rotation induced errors are avoided. It has the further advantage that it allows detection of large overlay errors in the y-direction, which may arise due to an alignment error commonly referred to as a capture error. Where a phase grating alignment mark is used, the signal used to provide alignment is sinusoidal. Assuming that in a pre-alignment operation the alignment mark is positioned sufficiently close to its intended position, an alignment unit will see a portion of the sinusoidal signal which comprises the peak which allows correct alignment. However, if the pre-alignment operation is not performed correctly, the alignment unit may see a portion of the sinusoidal signal which comprises an adjacent peak. Alignment to this adjacent peak will then occur, causing an error. The size of the error is dependent upon the separation of adjacent peaks of the sinusoidal signal, and is typically around 10 microns. The two dimensional gratings provide a means for detecting an overlay error caused by the capture error (i.e. an overlay error of around 10 microns). Referring to Figure 10a, in the absence of a capture error the product grating and resist grating are well separated. If capture error in the y-direction occurs then the gratings overlap, as shown in Figure 10b. The separation of the gratings is detected by monitoring coupling between the gratings, i.e. the coupled term of the diffraction signal (described previously in relation to Figure 7). The coupling shows up as a spatial beat frequency that can be detected by detectors of the metrology unit (the frequency is $|16/N-16/M|$). A negligibly low level of coupling will be seen between the gratings shown in Figure 10a, thereby indicating that a capture error has not occurred. A strongly coupled signal indicates that a capture error has occurred. In order for overlay of the grating to occur in the presence of a capture error the pitch Q must be properly chosen. For example a pitch Q

which is equal to one third of the expected capture error will give a complete overlap of the two gratings if a capture error occurs.

The gratings shown in Figure 9 comprise three product parts and two resist parts. It will be appreciated that different numbers of parts may be used, the only constraint being that both parts must have the same axis of symmetry in the x-direction if rotation induced errors are to be avoided. This means that the minimum number of parts is two product parts and one resist part or two resist parts and one product part.

The two dimensional gratings shown in Figure 10 provide easy and robust detection of capture errors. It will be appreciated that the pitch in the y-direction may be selected to provide detection of other sized errors.

In the above description it is noted that a negligibly low level of coupling will be seen between the gratings shown in Figure 10a. The reason why the coupling is not zero is explained in relation to Figure 11, which is a cross-sectional side view of the gratings shown in Figure 10a. From Figure 11 it can be seen that there is a significant separation in the z-direction between the product grating and the resist grating. This is may be because there is a layer of oxide above the product grating, or may be due to several other product layers being located over the product grating. Light used to illuminate the gratings for metrology measurements will diverge a little between the resist and product layers as shown, thereby introducing some coupling between the gratings.

If it is desired to avoid the coupling shown in Figure 11 a simple modification of the resist grating may be made. The modification, shown in Figure 11, comprises introducing alternating shifts Δx of the grating in the x-direction. When this grating configuration is used, the N^{th} order of the shifted gratings experiences a phase shift of:

$$\Delta\varphi_N = 2\pi\frac{MN}{16}\Delta x$$

When $\Delta\varphi_N = \pi$ the N^{th} order of the shifted gratings is in anti-phase with the unshifted gratings so that the N^{th} order will vanish, thereby eliminating the coupling. This allows high diffraction orders to be eliminated so that they do not introduce measurement errors at the detectors of the metrology unit. The method requires that illumination of the gratings is symmetric, something which is achievable in practice.

As described further above errors of the position of the wafer stage Δ_{stage} are cancelled out by the measurement performed using the metrology unit. There is however a second error which may reduce the accuracy of the metrology measurement. The second error is referred to as the sensor error ε (sometimes this is referred to in the art as the tool induced

shift) . Whilst the wafer stage position error Δ_{stage} is caused by the wafer stage not being located at the precise location that it is believed to occupy, the sensor error ε is caused by the fact that the optics of the metrology unit are not perfect . Imperfections of the optics of the metrology unit mean that the position of a diffraction grating as measured by a first detector of the metrology unit is not exactly the same as the position of the diffraction grating as measured by a second detector of the metrology unit, the optics having slightly displaced the diffraction patterns generated by the diffraction grating.

Where metrology is being performed based upon two gratings having different pitches (described above), the sensor error ε in the SbO calibration of the sensor can be eliminated by printing two pairs of gratings. The first pair has the M^{th} order in the resist layer and the N^{th} order in the product layer. The overlay measured with this pair is:

$$OV_1 = SbO_{n,m} + \varepsilon$$

In the second pair, the gratings are interchanged: the N^{th} order is in the resist and the M^{th} order grating is in the product layer. The overlay is:

$$OV_2 = -SbO_{n,m} + \varepsilon$$

The real SbO (i.e. overlay) is determined by:

$$SbO_{n,m} = OV_1 - OV_2$$

The method eliminates sensor errors ε in the calibration of the metrology unit.

Where metrology is being performed based upon two gratings having the same pitch (described further above), the sensor error ε in the SbO calibration of the sensor can be eliminated by printing two pairs of gratings together with a single grating. Each pair of gratings comprises a grating in the product layer and a grating in the resist layer. The single grating is provided in the resist layer (it will be appreciated that it could be provided in the product layer). The first pair of gratings includes a deliberate shift D in the x-direction between the gratings, and the second pair of gratings includes a deliberate shift $-D$ in the x-direction. Three shift between order SbO measurements are made, yielding the following:

$$SbO_1 = k(OV + D) + \varepsilon$$
$$SbO_2 = k(OV - D) + \varepsilon$$
$$SbO_3 = \varepsilon$$

where OV is the overlay and k is a constant that relates the shift between orders to the overlay. The third measurement yields the sensor error ε directly, since if there was no

error the shift between order would be zero (only one position is being measured). The two remaining unknowns k and OV can be determined using the first and second measurements, on the assumption that there is a linear relationship between the shift between orders and the overlay over the range of measured values.

In a further alternative embodiment of the invention an asymmetry is provided between a grating in a product layer and a grating in a resist layer via a deliberate offset between the gratings, as described further above, with the further addition that the lines of the gratings are provided with a substructure. The substructure of one of the gratings includes a phase jump. The combination of the high spatial frequency and the phase jump has the effect of significantly increasing the sensitivity of the metrology measurement. An advantage of using substructure in this way is that the substructure may be arranged to have dimensions and densities more similar to device features than conventional phase gratings, such that the measured overlay more accurately reflects the overlay of the device features.

Referring to Figure 13, a first grating p is provided in the product layer of a wafer and a second grating r is provided in the resist layer of the wafer. Figure 13, which is cross-sectional, shows in an upper region three periods of the gratings (the grating pitch is P), and in a lower region shows in detail a central portion of a single grating period. Each grating is provided with a grating substructure. The substructure of the product grating is continuous, whereas the substructure of the resist grating includes a 180 degree phase jump (it will be appreciated that the phase jump may be provided in the product grating instead of the resist grating). The 180 degree phase jump comprises a line of the resist grating which has double the length of other lines of the resist grating. The phase jump has the effect that, relative to the product grating, a rising edge of the resist grating will become a falling edge of the resist grating. In the absence of an overlay error the product grating and the resist grating are symmetric about a line of symmetry s.

The pitch g of the substructure, shown in Figure 13, of the gratings is chosen to be near to the limit of resolution of the lithographic projection apparatus (typically of the order of hundreds of nanometers). It will be appreciated that this number may in the future be significantly smaller as the resolution of lithographic projection apparatus improves. The substructure is sufficiently large relative to the wavelength of the illumination that diffraction occurs and propagates between the product layer and the resist layer. However, the substructure is sufficiently small that the diffraction from the substructure is not seen by the detectors of the metrology unit (for example because the diffraction is at a very large angle to the normal and is not collected by the lens L1 (see Figures 3 and 4)). Since

diffraction from the substructure either does not occur or is not seen, the sensor effectively sees the substructure as mirrors with a complex reflection coefficient r.

The complex reflection coefficient depends upon the relative positions of the resist and product layer substructures. If overlay is perfect, then the complex reflection coefficient of the left side substructure will be the same as the complex reflection coefficient of the right side substructure. This is represented schematically in Figure 14, which shows the intensity of light incident on a detector of the metrology unit. If a negative overlay error occurs, i.e. the resist layer is shifted to the right, then the complex reflection coefficient of the left side substructure will be different than that of the right side substructure. This asymmetry will be detected as a difference in detected intensity at the detectors of the metrology unit. Since the difference in intensity arises from the complex reflection coefficient, its sign will not always consistently agree with the sign of the overlay error. Figure 14 shows the amplitude of the near field (or equivalently the phase) of light diffracted from the gratings. The difference of phase in the near field is seen, when the orders are combined at a detector, as a change of the measured position. This change of the measured position is diffraction order and wavelength dependent.

The detected shift is dependent upon the diffraction order and/or wavelength detected by the metrology unit, and so can be used to measure overlay as described above. The detected shift is much greater than the overlay error, and this means that very small overlay errors may be detected using the metrology unit.

Mathematically the effect of the substructure can be expressed as follows: In the case of a small overlay error the reflection coefficient of the left and right halves will vary differently according to:

$$r_{left} = r_0 + \Delta r_1(x)$$
$$r_{right} = r_0 - \Delta r_1(x)$$

The resulting left-right asymmetry will create an easily measurable shift between orders. The complex reflection change is periodic with the pitch of the segmentation, which is a fraction of a micron. This means that an overlay error greater than the substructure will be incorrectly measured by the metrology unit.

The substructure is calibrated using two pairs of gratings and a single grating to determine the values of:

$$SbO_1 = k(OV + D) + \varepsilon$$
$$SbO_2 = k(OV - D) + \varepsilon$$
$$SbO_3 = \varepsilon$$

in same manner as described further above.

In a further alternative embodiment of the invention an asymmetry is provided in a single grating by including on the grating bearing mask (MA in Figure 1) high frequency substructures each provided with a 90 degrees phase jump, as shown in Figure 15. Adjacent lines of the grating are provided with substructures which have 90 degree phase jumps of opposite signs. The effect of the phase jumps is that, at the wafer surface, each line of the grating is shifted if the grating is not correctly focussed (this effect is described in US2002/0021434, incorporated herein by reference). The shift is dependent upon the sign of the phase jump, so that adjacent periods of the grating are shifted in opposite directions as a result of defocus. The asymmetry is measured by the metrology unit by comparing the shift caused by the asymmetry for different orders of diffraction and/or for different wavelengths (as previously mentioned, for ease of terminology this shift is referred to as the shift between orders or SbO).

The effect of the substructures is shown schematically in Figure 16. Three lines of a grating are shown in cross-section in Figure 16. The grating has a pitch P which is of the order of 10 micron. A central line has a width W_1 and is provided with a substructure G1 having a positive 90 degree phase jump. The pitch of the substructure is of the order of a few hundred nanometers. Adjacent lines have a width W_2 and are provided with substructures G2 having negative 90 degree phase jumps. The spacing between the substructures is a few microns, and the average width $\overline{W}$ of the gratings is a few microns.

If the grating (including the substructures) were to be perfectly focussed then the lines would be periodic (for example having a separation as shown in Figure 16). However, if the grating (including the substructures) were to be defocused then the lines would be shifted in opposite directions as indicated by the arrows in Figure 16. Without defocus the shift caused by the substructures is zero, and the grating is perfectly symmetric which yields a zero Shift between Orders (SbO). However, defocus introduces asymmetry since G1 and G2 shift in opposite directions over a distance Δx. This asymmetry shows up as a SbO that can be measured with the metrology unit as described below.

The sensitivity of the focus metrology can be tuned using the width of the gratings G1 and G2. It is shown that sensitivity can be made very large at the expense of signal strength.

The substructures G1 and G2 generate only zero diffraction orders and to first order can therefore be approximated as though they behave as plane surfaces with a complex reflection coefficient r_1. The area between G1 and G2 has a complex reflection coefficient r_0. W_1 and W_2 is split into an average part and a differential part:

$$W_1 = \overline{W} + \Delta W$$
$$W_2 = \overline{W} - \Delta W$$

Figure 17 shows the calculated sensitivity (i.e. the ratio of the measured shift to the real shift) as a function of ΔW for the 1st and 3rd order.

For small values of ΔW the measured position becomes very large. Moreover, the 1st and 3rd orders move in opposite directions, which increases the SbO even further. For ΔW=4 (arbitrary units) the sensitivity becomes 1 for both orders and the SbO becomes therefore zero. This is not surprising since this case corresponds to the situation where G2 has vanished so that the entire grating remains symmetric in the presence of defocus.

At first sight it may seem tempting to choose small values of ΔW. However, there is a price to pay: the strength of the detected signal decreases as ΔW is reduced. Figure 18 shows the normalized detected signal strength as a function of ΔW for the 1st and 3rd diffraction order. Here the signal strength has been normalized. At the same time, when the signal strength becomes very small, reticle write errors and surface roughness may limit the accuracy. The signal strength rapidly decreases for small values of ΔW. This is intuitively understandable since when ΔW is small the grating starts to behave as a grating with a pitch of P/2 instead of P. However, to some extent this can be compensated by making use of the large dynamic range of the phase grating detection used by the metrology unit. If it is assumed that a signal loss of a factor of 10 is acceptable (normalised signal strength=0.1.

It will be appreciated that it is not necessary that every period of the grating is provided with the above described substructures. All that is required is sufficient amounts of substructures to allow the shift between orders to be measured with a desired accuracy.

To first order, the SbO is insensitive to stage drift and stage vibrations so this method is particularly useful for low quality scanning stages.

In a further embodiment of the invention, a shift between orders is used to measure the critical dimension (CD) of patterns exposed on a wafer (critical dimension refers to the resolution of features exposed on the wafer). The method is based upon a metrology target which comprises three different regions, shown in Figure 19. The regions are an unexposed (i.e. raised) region *u*, a region having a substructure *s*, and an exposed (i.e.

recessed) region *e*. The three regions together form one period of an asymmetric grating which has a pitch of 4P (where P is of the order of microns). The substructure *s* has a pitch which is comparable near to the limit of resolution of the lithographic projection apparatus; in this case this is set at P/5 for ease of modeling. The unexposed region *u* and exposed region *e* both have a width of P, whereas the substructured region *s* has a width of 2P. The position of the grating is measured using a metrology unit of the type shown in Figure 20. Referring to Figure 20, a broadband coherent light source 200 generates a collimated beam of light which passes through an opening in a 45 degree mirror 201, and is focussed by a lens 202 onto a grating 203 (the grating is of the type shown in Figure 19). Light diffracted by the grating 203 is collimated by the lens 202, reflected by the 45 degree mirror and focused by a second lens 204 onto a set of scanning transmissive reference gratings 205. Light which passes through the transmissive reference gratings 205 is collimated by a third lens 206 onto a spectrometer grating 207. The spectrometer grating 207 diffracts the light at angles determined by the wavelength of the light. The diffracted light is focussed by a fourth lens 208 onto a detector array 209. In a preferred embodiment, as shown, the metrology unit further comprises conventional reflectometer hardware 210 and a polariser 211 used to control the linear polarisation of the light passing to the grating 203. The conventional reflectometer hardware 210 is well known to those skilled in the art, and therefore is not described here. The reflectometer hardware may be used t obtain additional metrology measurements in a conventional manner.

The 0-th order of light scattered by the grating 203 is retro-reflected and passes to the standard reflectometer hardware. This light is detected and processed in a manner that is analogous to the regular reflectometers.

It will be seen from Figure 20 that three scanning transmissive reference gratings 205 are provided adjacent one another. This is done to allow the measurement of different diffraction orders at the detector array 209.

Referring again to Figure 19, the grating provided can be seen to be asymmetric. Furthermore, the asymmetry of the grating changes as a function of CD. The asymmetry is accurately detected as a shift between Orders (SbO) or a Shift between Colors (SbC) by the metrology unit of Figure 20, thereby providing a measurement of the CD.

The effect of a change of CD can be understood intuitively with reference to Figure 19. If the CD were to improve to for example P/12.5 (ΔCD= -P/50), then the 'centre of gravity' of the grating (i.e. the centre of the grating as measured by the metrology unit) would be shifted to the left. In other words, the relative sizes of the contribution of light

diffracted by the line u and the substructured region s of the grating g will change, less light being seen from the substructured region s. The movement of the centre of gravity of the grating g is dependent upon the diffraction order and the wavelength of the light diffracted from the grating g. This means that, provided a calibration of the relative movements for different orders (or wavelengths) has been performed, a measurement of CD is obtained by looking at the shift between orders (or wavelengths).

An extreme instance of the intuitive example is shown in Figure 21. Referring to the upper half of Figure 21, a CD of zero (ΔCD= -P/10) will lead to no substructure being present such that the centre of gravity of the grating g will be measured as the centre of the line u of the grating. In an opposite extreme, a CD of P/5 (ΔCD= +P/10) will lead to the substructure merging such that the centre of gravity of the grating g will be measured as the midpoint between the beginning of the line u and the end of the merged substructured region s. Thus, a change of CD of P/5 will be seen as a shift of P by the metrology unit.

It should be noted that the configuration of the grating g shown in Figures 19 and 21 is just an example. In practice, many different configurations are possible, as will be apparent to the skilled reader.

The overlay metrology embodiments of the invention described above are generally described in terms of comparison of a product layer grating and a resist layer grating using a metrology unit which is used after development and baking of the resist (S8 in Figure 2), the metrology unit being typically located some distance away from the lithographic projection apparatus (wafers are carried from the lithographic projection apparatus to the metrology unit via a conveyor known as a track). However, it will be appreciated that the invention may be used to obtain overlay metrology measurements at other stages of the lithographic process cycle. For example, the metrology unit may be located within the lithographic projection unit and used to obtain metrology measurements for two previously processed product layers, or for a product layer and a resist layer bearing latent images.

In order to obtain overlay metrology measurements for two previously processed product layers, i.e. after etching and/or processing, the two layers must include gratings provided with some form of asymmetry (the asymmetry may be in any of the forms described above). A layer of resist is applied to the wafer in the conventional way, to allow exposure of a new layer, and the wafer passes to the lithographic projection apparatus. Prior to exposure of the new layer the metrology unit is used to obtain metrology measurements via the asymmetry present in the gratings, using one or more of the methods described above. It will be appreciated that the metrology measurements may be obtained after exposure.

Conveniently, the metrology unit may comprise a unit which is also used to obtain alignment information for the subsequent exposure (i.e. separate metrology and alignment units are not required). It will be appreciated that overlay metrology measurements for several preceding product layers may be obtained, via comparison of gratings having an appropriate asymmetry. In general terms, prior to exposure of layer n+1, marks exposed in previous layers n, n-1 (or n-2,…,n-m) can be measured, allowing overlay metrology between layers n and n-1 (or n-2,…,n-m and combinations thereof).

Conveniently, the overlay metrology measurements may be obtained during alignment of the wafer for exposure, i.e. when the alignment unit is located over a given alignment grating for alignment purposes, it may obtain a first measurement based solely upon that grating in to provide alignment, and may obtain a second measurement based upon a grating located in a layer above or beneath the alignment grating (or based upon a combination of both gratings) the second measurement being used to provide overlay metrology measurements. Where a dual stage lithographic apparatus is used (i.e. the wafer is mapped in a separate stage prior to exposure, as described for example in EP1037117) the overlay metrology measurement may be performed without any reduction of productivity.

Using the method in this way is advantageous because it allows overlay metrology measurements to be performed for every wafer, thereby minimizing the possibility that a non-yielding wafer or die is not detected. This is favorable compared to conventional arrangements in which overlay metrology measurements are performed for only a representative sample of wafers. The overlay metrology data provided may be used to provide an estimation of corrections to be applied to subsequent batches for a given resist layer n (feedback). In addition, in instances where processing steps are comparable, may be used to provide an estimation of corrections to be applied to a subsequent layer (feedforward).

Overlay metrology which embodies the invention may be performed for latent images. The latent images may be images which have been exposed in resist, i.e. without post exposure bake. However, in some instances it may not be possible to resolve such images, in which case a post exposure bake may be used.

In addition to overlay metrology the invention may be used, as described above, to provide focus metrology or critical dimension metrology. Where this is done the focus or critical dimension metrology measurement may be performed for a grating in a process layer or a grating in a resist layer. The metrology measurements may be performed for latent images

before or after post exposure bake. The metrology unit may be in any of the locations mentioned above.

It is known from the art that it is not necessary to use a grating in order to obtain diffraction. Diffraction may be obtained by directing illumination onto a suitably dimensioned single feature (typically the feature is of the order of the wavelength of the illumination) or other suitably dimensioned target. The use of diffraction gratings is preferred for the described embodiments of the invention because they provide strong diffraction signals. However, it will be appreciated that the invention may be implemented using targets which are not diffraction gratings. For example, consider the embodiment of the invention described in relation to figure 5. The target shown comprises four lines of a product grating and four lines of a resist grating. If three lines of each grating are removed from the target, then the target will comprise a single line in the resist layer located over a single line in the product layer. Light directed at the target will be diffracted by the target. Different diffraction orders and/or wavelengths will be detected by the metrology unit. Differences in the position of the target as measured for different diffraction orders and/or wavelengths may be used to measure overlay, in the manner described further above.

It will be appreciated that other embodiments of the invention which have been described in relation to diffraction gratings may also be implemented using single features or other suitably dimensioned targets.

What is needed in order for the invention to function correctly is targets which include some degree of asymmetry. If a target is entirely symmetric then it will not provide metrology according to the invention. The following is a mathematical explanation of why the asymmetry is required:

Consider an isolated feature target that is symmetric around a position x_0 and is illuminated with a light beam that is also symmetric around x_0. By virtue of symmetry considerations, the near-field that is created by this configuration must also show the same type of symmetry around x_0:

$$E_e^{(nf)}(x - x_0; \lambda) = E_e^{(nf)}(-x - x_0; \lambda)$$

Here the dependency of the near field on the wavelength λ is explicitly indicated. For simplicity only 1 dimension (x) is considered, but an extension to 2 dimensions, however, can easily be made. The propagation of the field defined above obeys the wave equation for homogeneous media. The resulting field distribution that is very far away from the scattering target is called the far-field. It is shown in various text books on this subject [e.g.

J.W. Goodman; Introduction to Fourier Optics; McGraw-Hill;] that this far-field is the Fourier transform of the near field. Again by virtue of symmetry, this far-field must also possess symmetry:

$$E_e(\theta;\lambda,x_0)=E_e(-\theta;\lambda,x_0)$$

$$|E_e(\theta;\lambda,0)|\exp[j\varphi_e(\theta;\lambda)]\exp\left[-2\pi j\frac{\sin(\theta)}{\lambda}x_0\right]=|E_e(-\theta;\lambda,0)|\exp[j\varphi_e(-\theta;\lambda)]\exp\left[2\pi j\frac{\sin(\theta)}{\lambda}x_0\right]$$

$$|E_e(\theta;\lambda,0)|\exp[j\varphi_e(\theta;\lambda)]\exp[-jkx_0]=|E_e(-\theta;\lambda,0)|\exp[j\varphi_e(-\theta;\lambda)]\exp[jkx_0]$$

where the subscript 'e' denotes an even function of the far-field angle θ. and $k=2\pi\sin(\theta)/\lambda$ is called the spatial angular frequency. The 2nd expression in the equations above merely uses the Fourier shift theorem: A shift in the space domain results in a linear phase shift in the frequency domain. In other words, a symmetric target always has a symmetric amplitude of the far-field. Moreover, the phase φ_e of the far-field is also symmetric and the only anti-symmetric component that can exist is a linear phase shift that is introduced by a displacement of the target.

Note that this treatment is valid for gratings and isolated objects. It is basically a mathematical formulation of an optical alignment sensor concept. Basically, all existing optical alignment sensors compare the phase difference between a selected range of negative spatial frequencies $[-k_1\cdots-k_2]$ and a corresponding range of positive spatial frequencies $[k_2\cdots k_1]$. This phase difference is only a function of x_0 and independent of the even phase difference φ_e. This measurement is suitable for alignment, but does not provide metrology measurement.

All of the embodiments of the invention rely on the fact that the metrology unit measures the apparent position of an asymmetric (composite) grating for different orders/colors. A common factor in these embodiments is the fact that the grating asymmetry is a (non-linear) function of the metrology parameter that needs to be measured (Overlay, CD, lens aberration,...). This section will extend the mathematical formalism of the previous section to show that the grating-based ideas can be extended to non-periodic targets.

The near field created by an asymmetric target at position x_0 is generally also asymmetric. Mathematically, we can always decompose this near field in a symmetric (=even) and an anti-symmetric component (=odd):

$$E^{(nf)}(x-x_0;\lambda)=E_e^{(nf)}(-x-x_0;\lambda)+E_o^{(nf)}(-x-x_0;\lambda)$$

Here the subscripts 'e' and 'o' denote, respectively, even and odd complex functions with the property:

$$f_e(x) = f_e(-x)$$
$$f_o(x) = -f_o(-x)$$

Fourier transforming this near field, and using the linearity of a Fourier transform results in a far field that also consists of a symmetric (=even) and an anti-symmetric (=odd) part:

$$E(\theta;\lambda,x_0) = E_e(\theta;\lambda,x_0) + E_o(-\theta;\lambda,x_0)$$
$$E(\theta;\lambda,0) = \left\{\left|E_e(\theta;\lambda,0)\right|\exp\left[\mathrm{j}\varphi_e(\theta;\lambda)\right] + \left|E_o(\theta;\lambda,0)\right|\exp\left[\mathrm{j}\varphi_o(\theta;\lambda)\right]\right\}\exp\left[2\pi\mathrm{j}\frac{\sin(\theta)}{\lambda}x_0\right]$$
$$E(\theta;\lambda,0) = \left\{\left|E_e(\theta;\lambda,0)\right|\exp\left[\mathrm{j}\varphi_e(\theta;\lambda)\right] + \left|E_o(\theta;\lambda,0)\right|\exp\left[\mathrm{j}\varphi_o(\theta;\lambda)\right]\right\}\exp\left[\mathrm{j}kx_0\right]$$

According to the above-mentioned property of odd complex functions the phase and amplitude terms obey:

$$\left|E_{e,o}(\theta;\lambda,0)\right| = \left|E_{e,o}(-\theta;\lambda,0)\right|$$
$$\varphi_e(\theta;\lambda) = \varphi_e(-\theta;\lambda)$$
$$\varphi_o(\theta;\lambda) = \varphi_o(-\theta;\lambda) + \pi$$

Before proceeding with a practical interpretation of this rather abstract analysis, it is worthwhile to emphasize that this analysis is valid for any target. Moreover, the even and odd phase terms φ_e and φ_o are a function of the spatial frequency (=far-field angle θ) and the wavelength λ (i.e. differences between the terms will be seen by measuring a shift between orders).

Figure 21 shows a graphical interpretation for the situation when x_0=0 (i.e. the object is at its defined location). In that case the complex amplitudes of the symmetric part of the diffracted fields at 2 far-field angles θ and $-\theta$ are equal but depend on the chosen angle and the wavelength. The anti-symmetric complex fields are also shown in Figure 21 and their amplitudes and phase α relative to the even part also depend on the far-field angle and the wavelength.

The metrology unit does not distinguish between a symmetric and an anti-symmetric part of the far-field. It only measures the total field, which is the vectorial sum of the even and odd fields shown in Figure 21. In general terms, the metrology unit measures the phase difference ψ (see Figure 21) between mirrored spatial frequencies (or equivalently: far-field angles). The vectorial construction clearly shows that this will depend on the magnitudes and relative phases of the even and odd parts of the spectrum. Generally, a change in the asymmetry of the target will change the even and odd parts of the far field. This change is wavelength /far-field angle dependent, which results in a measurable position:

$$x_m(k,\lambda) = x_0 + \frac{\psi(k,\lambda)}{2}\frac{1}{k}$$

Here the subscript 'm' indicates that it concerns a 'measured' position which consists of 2 terms: the "true" position x_0 and the asymmetry offset. The true position is independent of wavelength and spatial frequency so we can eliminate this unknown term by measuring the position for 2 different colors and/or spatial frequencies ("diffraction orders" in case of gratings):

$$\Delta x(k_1,k_2,\lambda_1,\lambda_2) = \frac{\psi(k_1,\lambda_1)}{2k_1} - \frac{\psi(k_2,\lambda_2)}{2k_2}$$

Note that the vectorial construction shows that the contrast (i.e. the amplitude difference) could also be used. This, however, is not preferred since the asymmetry effects are generally quite small which leads to contrasts that deviate only slightly from unity.

Claims

1. A method of device inspection, the method comprising providing an asymmetric marker on a device to be inspected, the form of asymmetry of the marker being dependent upon the parameter to be inspected, directing light at the marker, obtaining a first measurement of the position of the marker via detection of diffracted light of a particular wavelength or diffraction angle, obtaining a second measurement of the position of the marker via detection of diffracted light of a different wavelength or diffraction angle, and comparing the first and second measured positions to determine a shift indicative of the degree of asymmetry of the marker.
2. A method according to claim 1, wherein the first and second position measurements comprise detection of diffracted light having different diffraction angles but the same wavelength.
3. A method according to claim 1, wherein the first and second position measurements comprise detection of diffracted light having the same diffraction angle but different wavelengths.
4. A method according to claim 1, wherein the first and second position measurements comprise detection of diffracted light having different diffraction angles and different wavelengths.
5. A method according to any preceding claim, wherein the marker comprises one or more diffraction gratings.
6. A method according to claim 5, wherein the one or more diffraction gratings are phase gratings
7. A method according to claim 5 or claim 6, wherein the marker comprises a first diffraction grating provided in a first layer of the device, and a second diffraction grating provided in a second lower layer of the device, the first diffraction grating and the second diffraction grating having the same pitch and being provided one over the other such that the light is diffracted by both of the gratings in combination, measured asymmetry between the diffraction gratings indicating overlay of the first and second layers.
8. A method according to claim 7 wherein lines of the first diffraction grating are narrower than lines of the second diffraction grating.

9. A method according to claim 7 or claim 8, wherein the shift is used to determine the overlay of the first and second layers.

10. A method according to claim 9, wherein the overlay is calibrated by using third and fourth diffraction gratings provided in the first and second layers respectively, the third and fourth diffraction gratings being provided adjacent the first and second diffraction gratings.

11. A method according to claim 10, wherein an overlay offset of a first sign is provided between the first and second diffraction gratings, and an overlay offset of an opposite sign is provided between the third and fourth diffraction gratings.

12. A method according to claim 11, wherein the magnitudes of the offsets are of the order of the largest desired overlay measurement.

13. A method according to claim 12, wherein the offsets are of the order of 100nm.

14. A method according to any of claims 10 to 13, wherein the overlay calibration is used to calibrate overlay measurements obtained using further diffraction gratings at other locations on the device.

15. A method according to any of claims 10 to 14, wherein in addition to the first, second, third and fourth diffraction gratings, fifth and sixth diffraction gratings are provided in the first and second layers respectively, the fifth and sixth diffraction gratings having a different offset used to increase the calibration accuracy of the overlay measurement.

16. A method according to any of claims 10 to 15, wherein a further diffraction grating is provided adjacent the other gratings, either in the first layer or the second layer, the method further comprising measuring the shift between orders for the further diffraction grating to determine a sensor error of the shift between order measurement.

17. A method according to any of claims 5 to 16, wherein the first and second diffraction gratings are provided with a substructure, the substructure of one of the diffraction gratings including a diffraction jump such that asymmetry arises in the diffracted light as a function of the relative positions of the substructures, the asymmetry being detected as a shift between orders.

18. A method according to claim 17, wherein the pitch of the substructure is of the order of the limit of resolution of a lithographic projection apparatus used to project the diffraction gratings onto the device.

19. A method according to claim 17 or claim 18, wherein the pitch of the substructure is sufficiently large relative to the wavelength of the illumination that diffraction occurs and propagates between the first layer and the second layer, but the pitch of the substructure is sufficiently small that diffraction from the substructure is not detected during measurement.

20. A method according to claim 17, wherein the first and second diffraction gratings are provided with an overlay offset of a first sign, the third and fourth gratings having the same substructure are provided, with an overlay offset of an opposite sign, the offsets being used to calibrate the shift between orders overlay measurement.

21. A method according to claim 20, wherein a further diffraction grating is provided adjacent the other gratings, either in the first layer or the second layer, the method further comprising measuring the shift between orders for the further diffraction grating to determine a sensor error of the shift between order measurement.

22. A method according to claim 5, wherein the marker comprises a first diffraction grating provided in a first layer of the device, and a second diffraction grating provided in a second lower layer of the device, the first diffraction grating and the second diffraction grating having different pitches each selected to give rise to strong diffraction at different diffraction orders, such that a measurement of the position of the first diffraction grating is provided by measuring one diffraction order and a measurement of the position of the second diffraction grating is provided by measuring the other diffraction order, the shift between the measured positions indicating the overlay of the first and second layers.

23. A method according to claim 22, wherein the pitches of the first and second diffraction gratings are selected such that light diffracted by both diffraction gratings will not yield a strong combined signal having the same frequency as a measured diffraction order.

24. A method according to claim 22 or claim 23, wherein the first and second diffraction gratings are provided one over the other.

25. A method according to claim 22 or claim 23, wherein the first and second diffraction gratings are spatially separated.

26. A method according to claim 25, wherein the first diffraction grating is located adjacent the second diffraction grating as a grating pair.

27. A method according to claim 22, wherein rotational errors are avoided by providing a second grating pair, comprising a third diffraction grating having the same pitch as the second diffraction grating and a fourth diffraction grating having the same pitch as the first diffraction grating, the second pair being laterally displaced relative to the first grating pair, in a direction transverse to lines of the gratings

28. A method according to claim 27, wherein one diffraction grating is divided into two rows which lie either side of the other diffraction grating, the division being along an axis transverse to the direction of lines of the diffraction gratings.

29. A method according to claim 28, wherein both the first diffraction grating and the second diffraction grating are divided into two or more alternating rows.

30. A method according to claim 29, wherein the first diffraction grating and the second diffraction grating have a common axis of symmetry which lies transverse to the direction of lines of the diffraction gratings.

31. A method according to claim 29 or claim 30, wherein the rows are arranged to form a diffraction grating having a pitch defined by the separation of the rows.

32. A method according to claim 31, wherein the method further comprises monitoring the strength of a beat frequency caused by coupling between light diffracted by the first diffraction grating and light diffracted by the second diffraction grating, to provide an indication of overlay in the direction parallel to the pitch defined by the separation of the rows.

33. A method according to claim 32, wherein the separation of the rows is selected such that an overlay error arising due to a capture error will give rise to strong coupling.

34. A method according to any of claims 28 to 30, wherein an offset is introduced into one of the diffraction gratings relative to the other diffraction grating, the size of the offset being selected to minimise coupling between light diffracted by the first diffraction grating and light diffracted by the second diffraction grating.

35. A method according to any of claims 22 to 34, wherein the method further comprises determining sensor error by providing in the first layer of the device

a third diffraction grating having the same pitch as the second diffraction grating, and providing in the second lower layer of the device a fourth diffraction grating having the same pitch as the first diffraction grating, the sensor error being eliminated by comparing the measured shift between orders for the first and second diffraction gratings and the third and fourth diffraction gratings.

36. A method according to claim 6, wherein the marker comprises one phase grating arranged to measure the focus accuracy of a lithographic projection apparatus, the method comprising providing on a mask of the lithographic projection apparatus a phase grating having a substructure which includes a phase jump of substantially 90 degrees, the phase jump being of opposite sign for adjacent periods of the grating, the pitch of the substructure being selected such that a focus error will cause the phase grating to move when projected onto the device by the lithographic apparatus, adjacent periods of the phase grating being moved in opposite directions giving rise to an asymmetry which is measured by the shift.

37. A method according to claim 36, wherein the relative widths of the adjacent periods of the phase grating are selected to be different such that the asymmetry is sufficiently large to be measured by the shift.

38. A method according to claim 5, wherein the marker comprises one diffraction grating arranged to measure the critical dimension of a lithographic projection apparatus, the method comprising providing on the device a diffraction grating having a substructure with a pitch at, or of the order of, the limit of resolution of the lithographic projection apparatus, the substructure being arranged to extend a line of the diffraction grating which renders the diffraction grating asymmetric, changes of the critical dimension modifying the effective reflectivity of the substructure thereby modifying the asymmetry of the diffraction grating, the modified asymmetry being detected as the shift between orders.

39. A method according to any preceding claim, wherein the inspection method is performed directly after exposure of the marker on the device.

40. A method according to any of claims 1 to 38, wherein the inspection method is performed after exposure and post exposure bake of the marker on the device.

41. A method according to any of claims 1 to 38, wherein the inspection method is performed after exposure and hard bake of the marker on the device.

42. A method according to any of claims 1 to 36, wherein the inspection method is performed after exposure and processing of the marker on the device.

43. A method according to any of claims 1 to 38, wherein the inspection method is preformed after application of a layer of resist onto the device and before exposure of that resist, the marker being provided in one or more processed layers of the device.

44. A method according to any preceding claim, wherein the method is performed for a device located within a lithographic projection apparatus, the position of the marker being used to provide alignment information for lithographic projection in addition to providing inspection of the device.

45. A device inspection apparatus, the apparatus comprising a light source arranged to direct light at an asymmetric marker provided on a device, a detector arranged to detect light diffracted from the marker with a particular wavelength or diffraction angle thereby providing a measurement of the position of the marker, a second detector arranged to detect light diffracted from the marker with a different wavelength or angle order thereby providing a second measurement of the position of the marker, and comparison means arranged to compare the measured positions to determine a shift indicative of the degree of asymmetry of the marker.

46. A device inspection apparatus according to claim 45, wherein the apparatus is located within a lithographic projection apparatus.

47. A device inspection apparatus according to claim 45, wherein the apparatus is located within a track connected to a projection apparatus.

48. A device inspection apparatus according to claim 45, wherein the apparatus is provided in a housing which is separated from the lithographic projection apparatus.

49. A device inspection apparatus according to any of claims 44 to 48 and configured to perform the method according to any of claims 1 to 43.

50. A device inspection apparatus, the apparatus comprising a light source arranged to direct light at a phase grating provided on a device, a detector arranged to

detect light diffracted from the phase grating, and processing means arranged to obtain inspection information using the detected diffracted light.

Abstract

A method of device inspection, the method comprising providing an asymmetric marker on a device to be inspected, the form of asymmetry of the marker being dependent upon the parameter to be inspected, directing light at the marker, obtaining a first measurement of the position of the marker via detection of diffracted light of a particular wavelength or diffraction angle, obtaining a second measurement of the position of the marker via detection of diffracted light of a different wavelength or diffraction angle, and comparing the first and second measured positions to determine a shift indicative of the degree of asymmetry of the marker.

[figure 3]

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Fig. 1

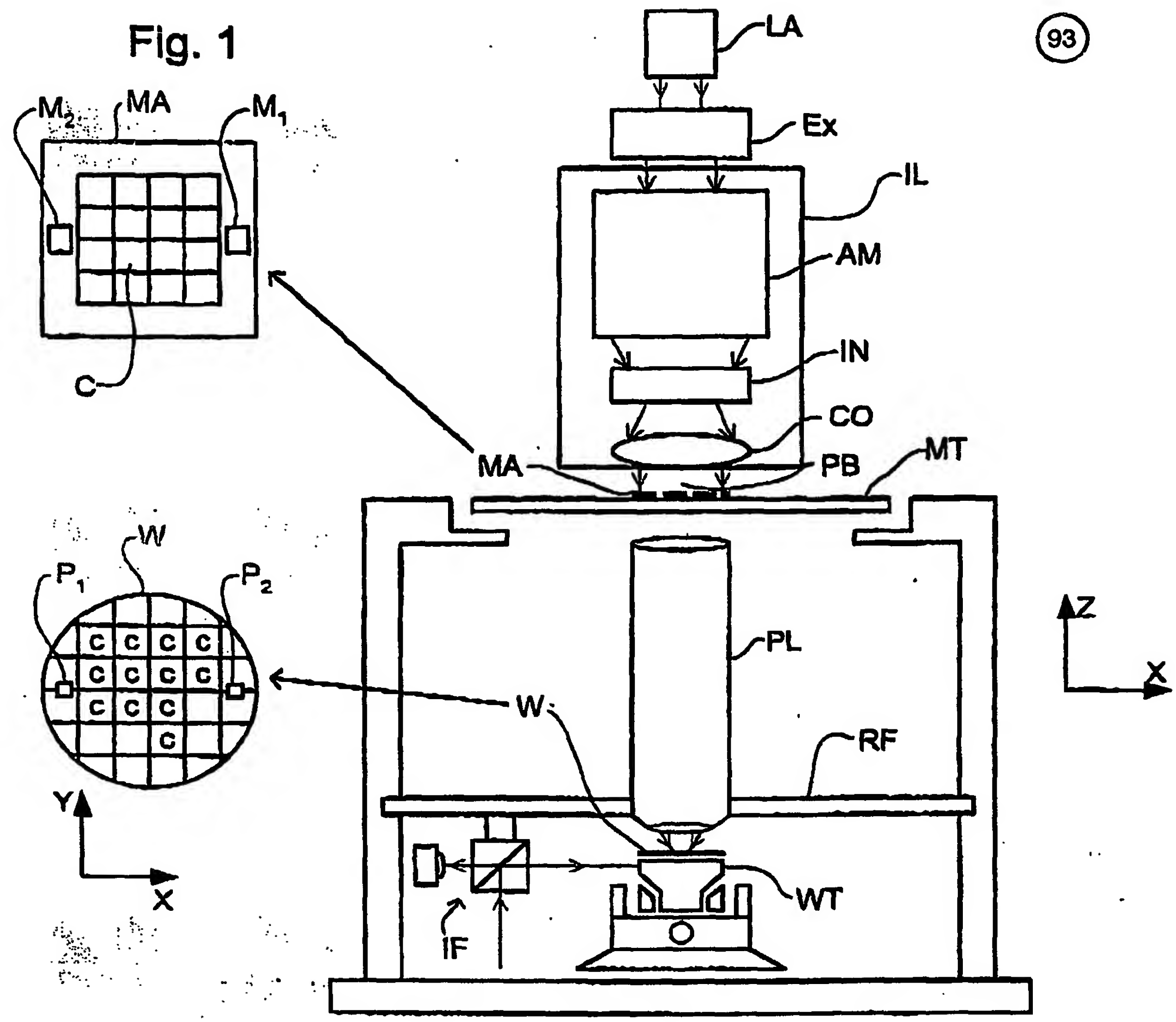
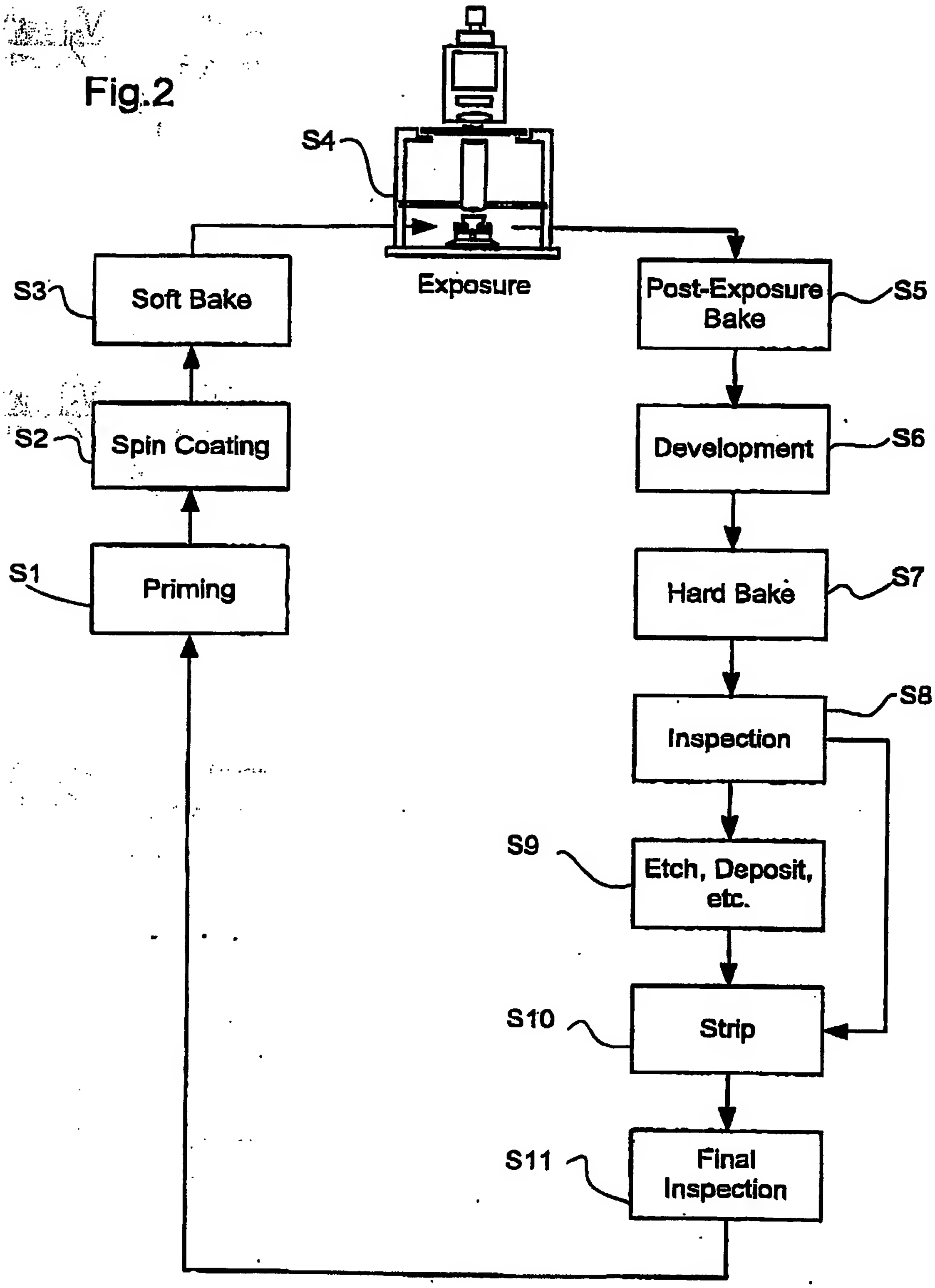


Fig.2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Exposure
S3
Soft Bake
S2
Spin Coating
S1
Priming
Post-Exposure Bake
S5
Development
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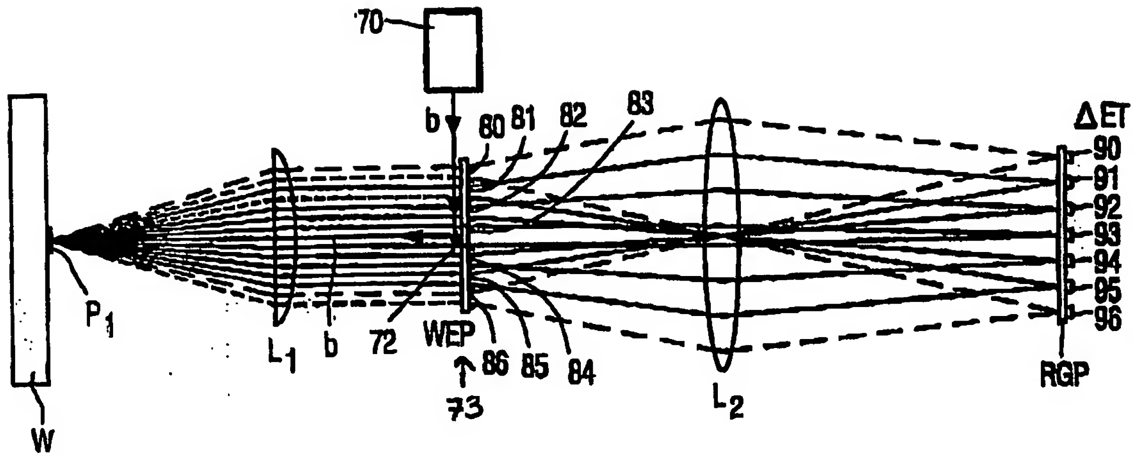
Hard Bake
S7
S8
Inspection
S9
Etch, Deposit, etc.
S10
Strip
S11
Final Inspection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b
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81
82
83
ΔET
90
91
92
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P1
L1
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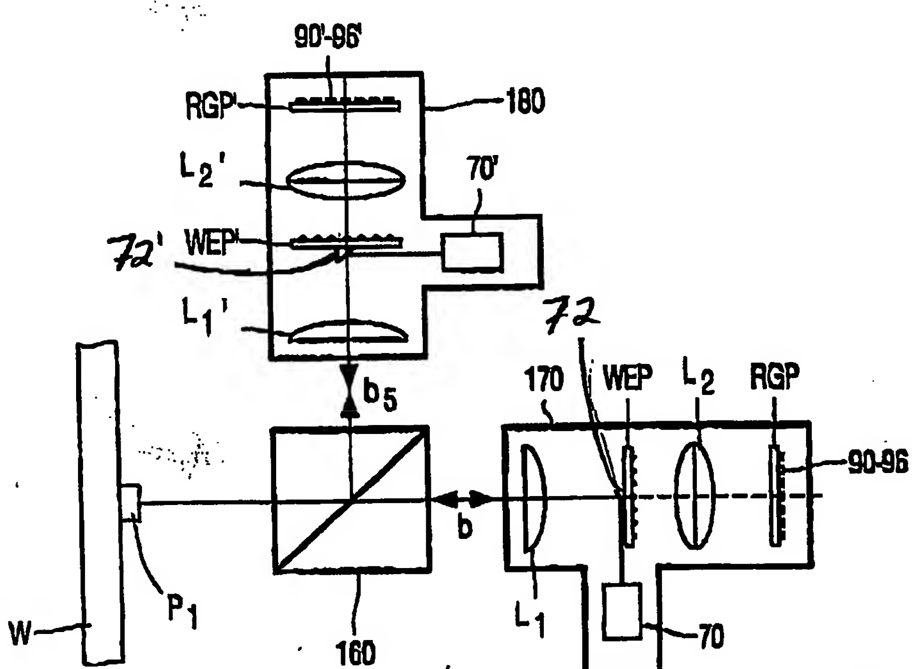
WEP
86
85
84
73
L2
RGP
W

FIG. 3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RGP'
180
L2'
70'
72'
WEP'
L1'
72
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WEP
L2
RGP
b5
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160
L1
70

FIG. 4

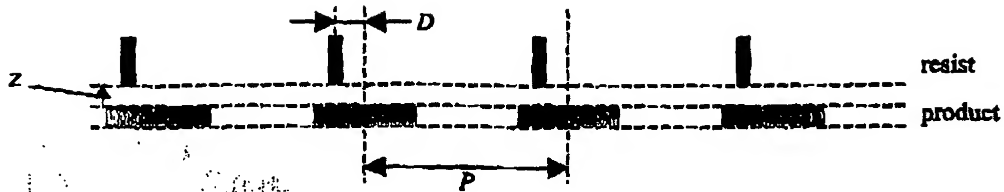


Figure 5

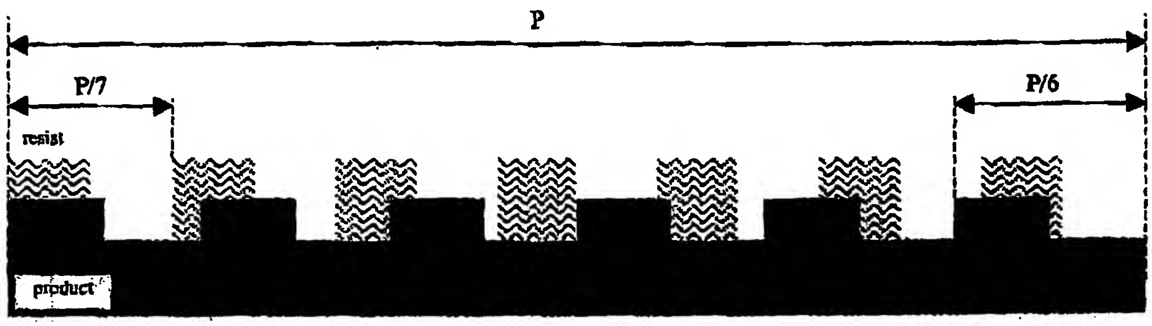


Figure 6

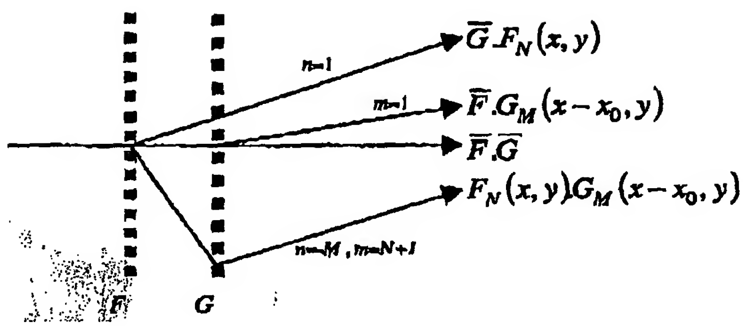


Figure 7

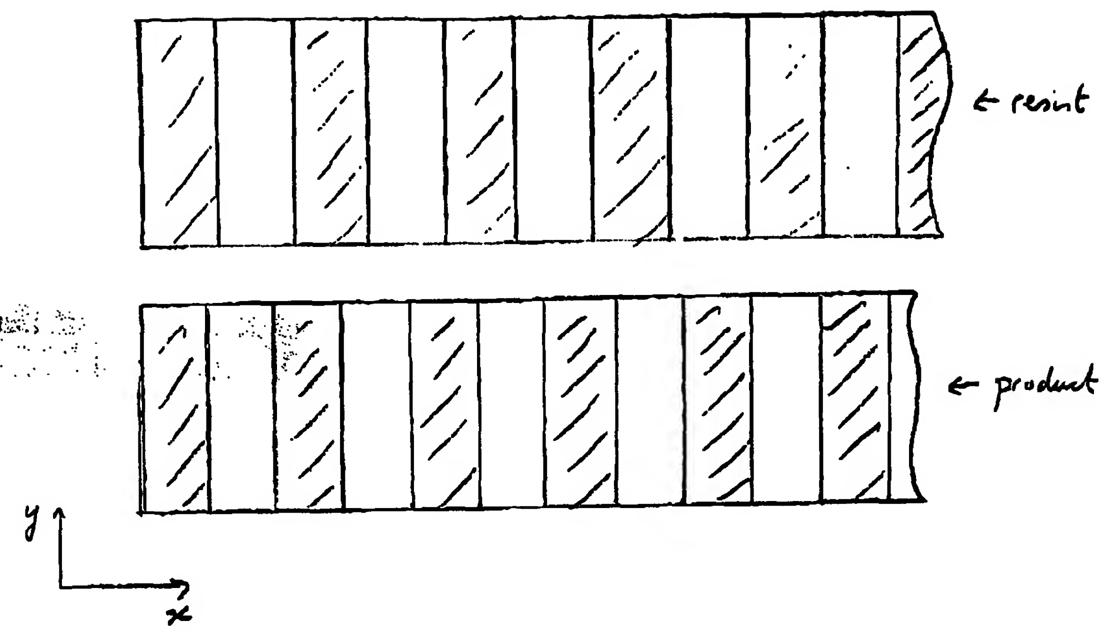


Figure 8

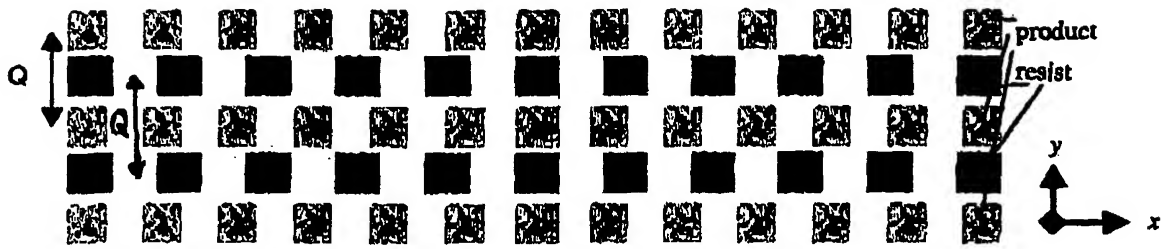


Figure 9

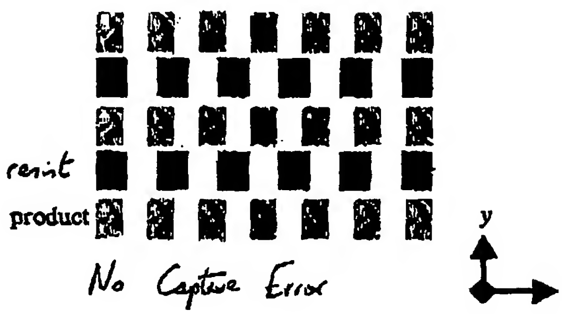


Figure 10a

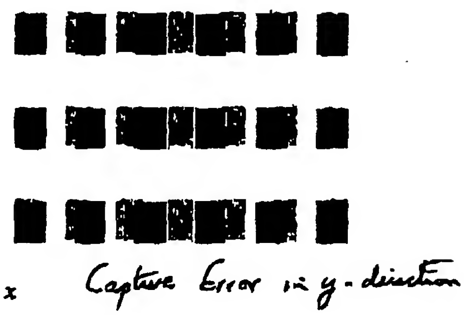


Figure 10b

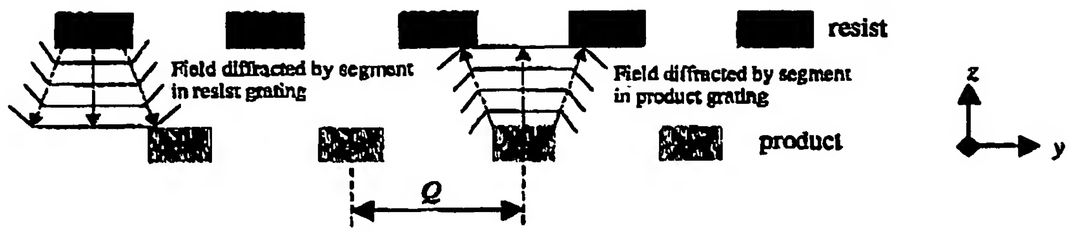


Figure 11

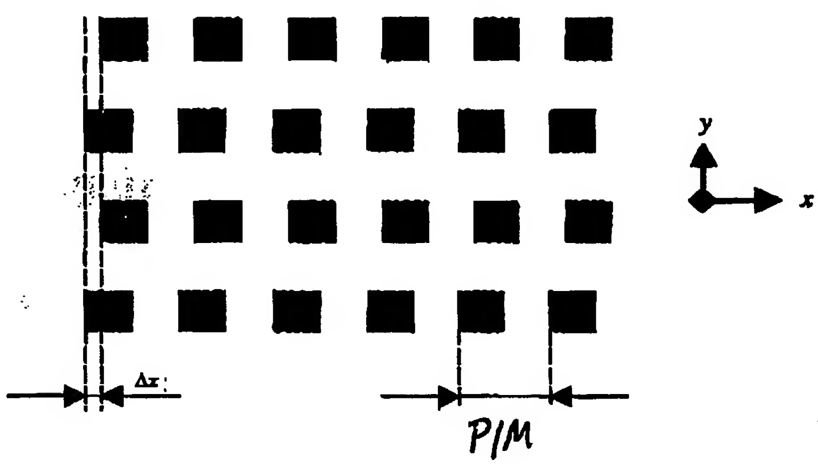


Figure 12

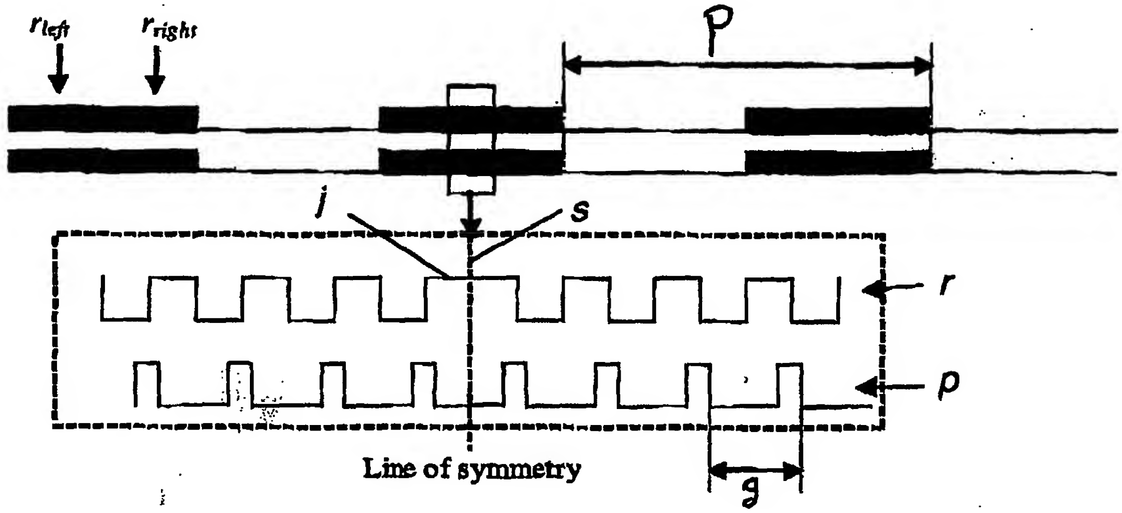


Figure 13

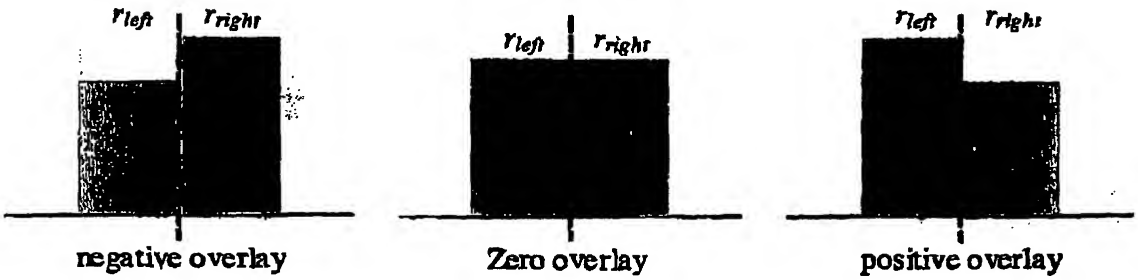


Figure 14

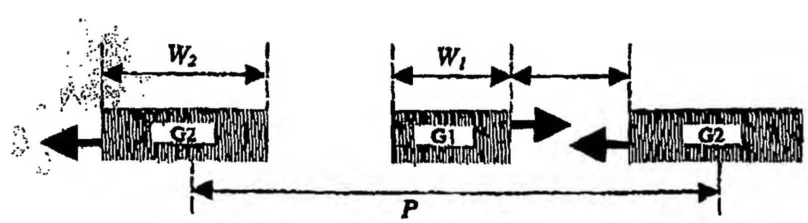


Figure 16

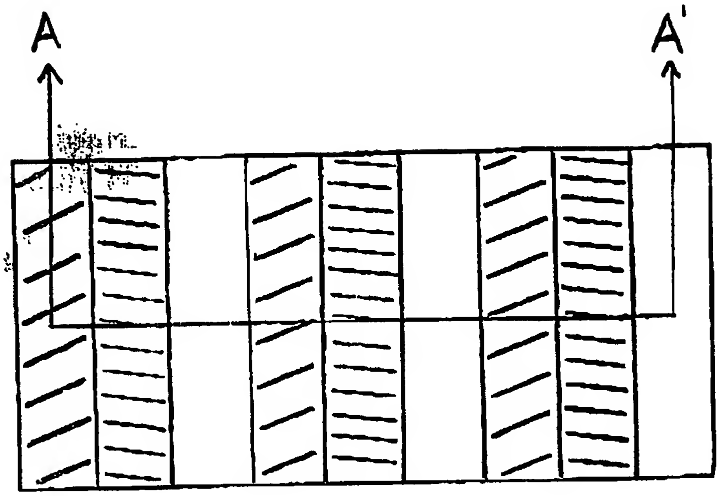


Figure 15a

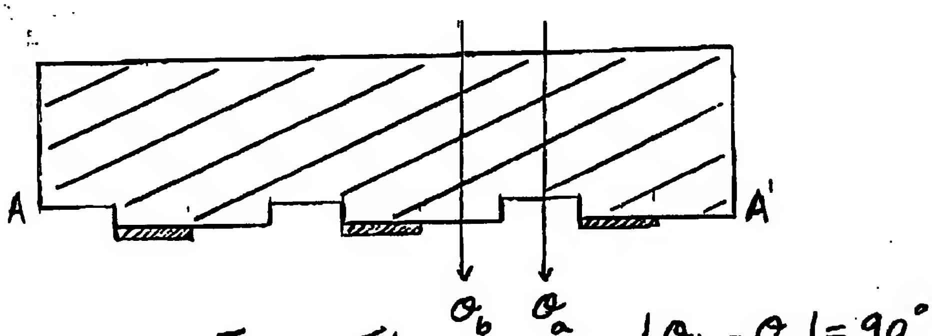


Figure 15b

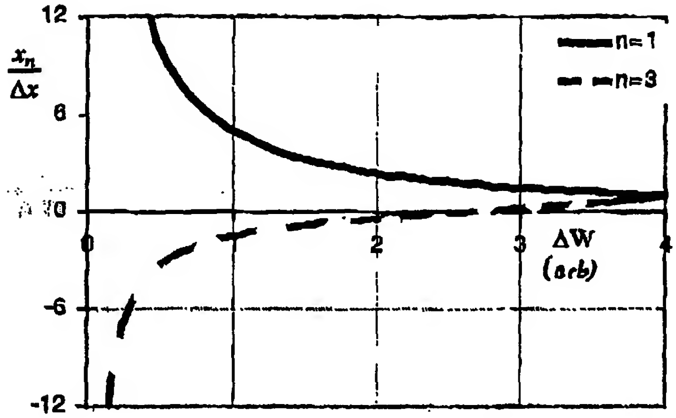


Figure 17

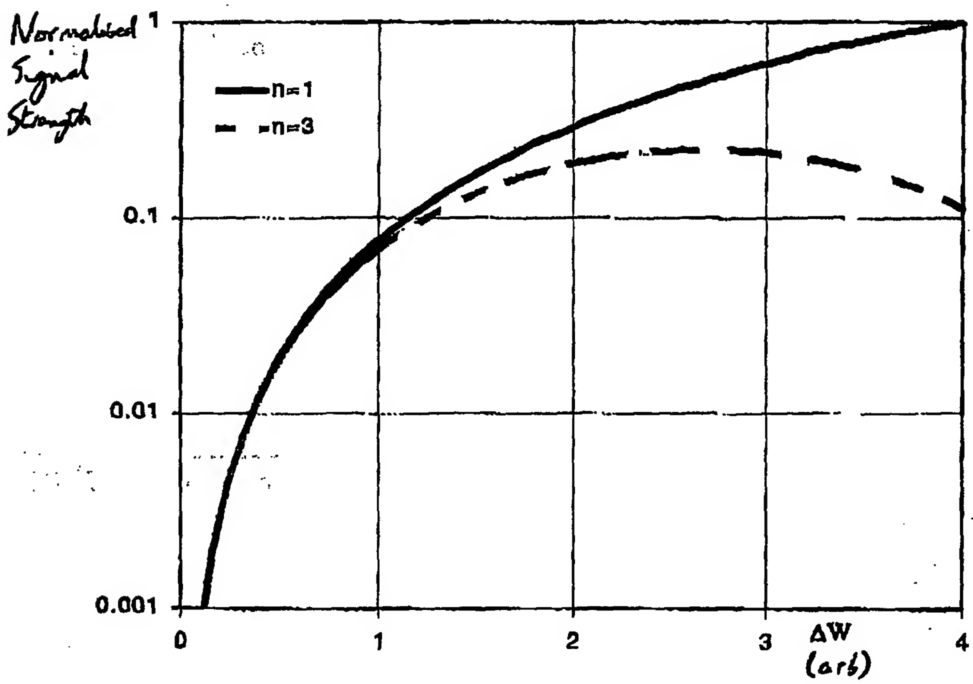


Figure 18

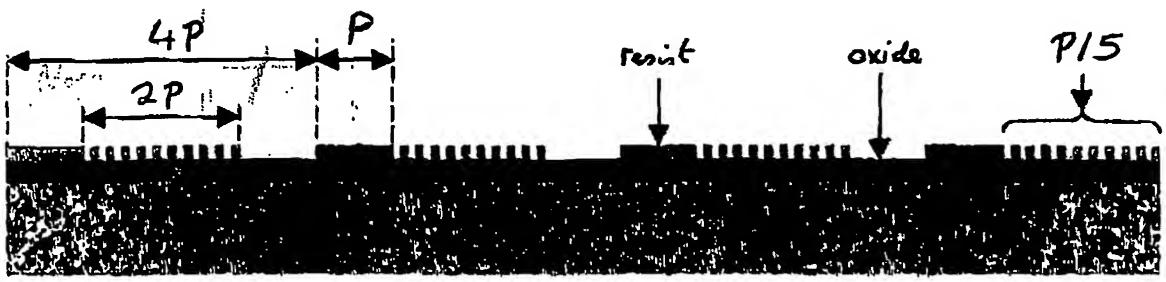


Figure 19

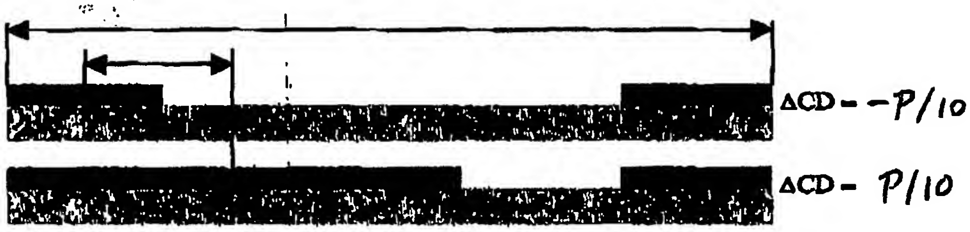
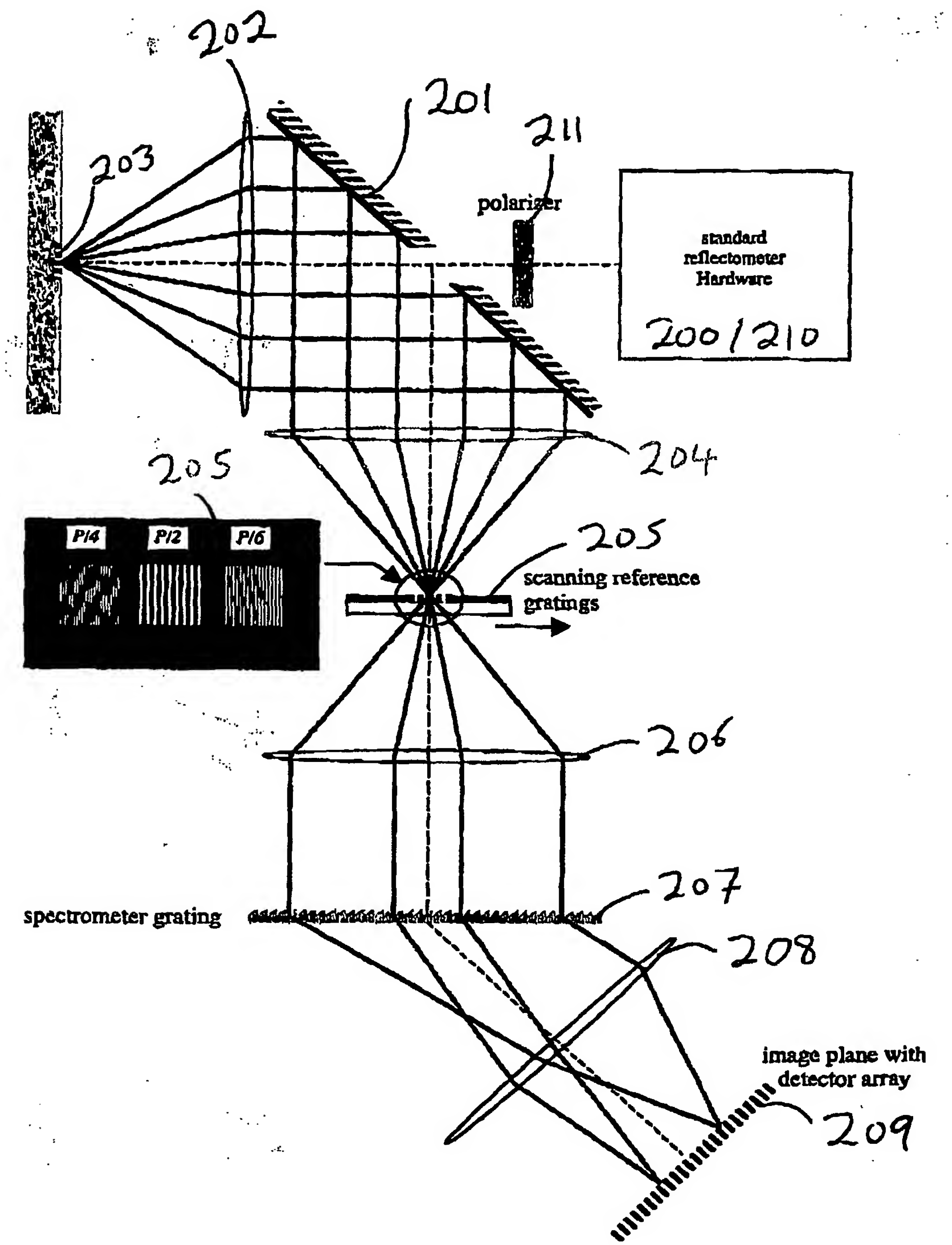


Figure 21


202
201
211
203
polarizer
standard reflectometer Hardware
200/210
204
205
P/4
P/2
P/6
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scanning reference gratings
206
207
spectrometer grating
208
image plane with detector array
209

Figure 20

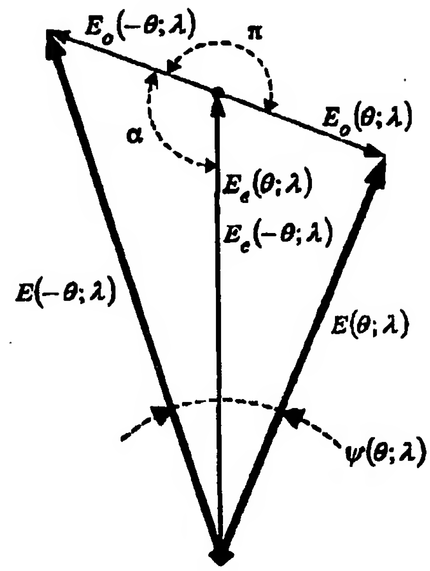
$E_o(-\theta;\lambda)$
π
$E_o(\theta;\lambda)$
α
$E_e(\theta;\lambda)$
$E_e(-\theta;\lambda)$
$E(-\theta;\lambda)$
$E(\theta;\lambda)$
$\psi(\theta;\lambda)$

Figure 22